

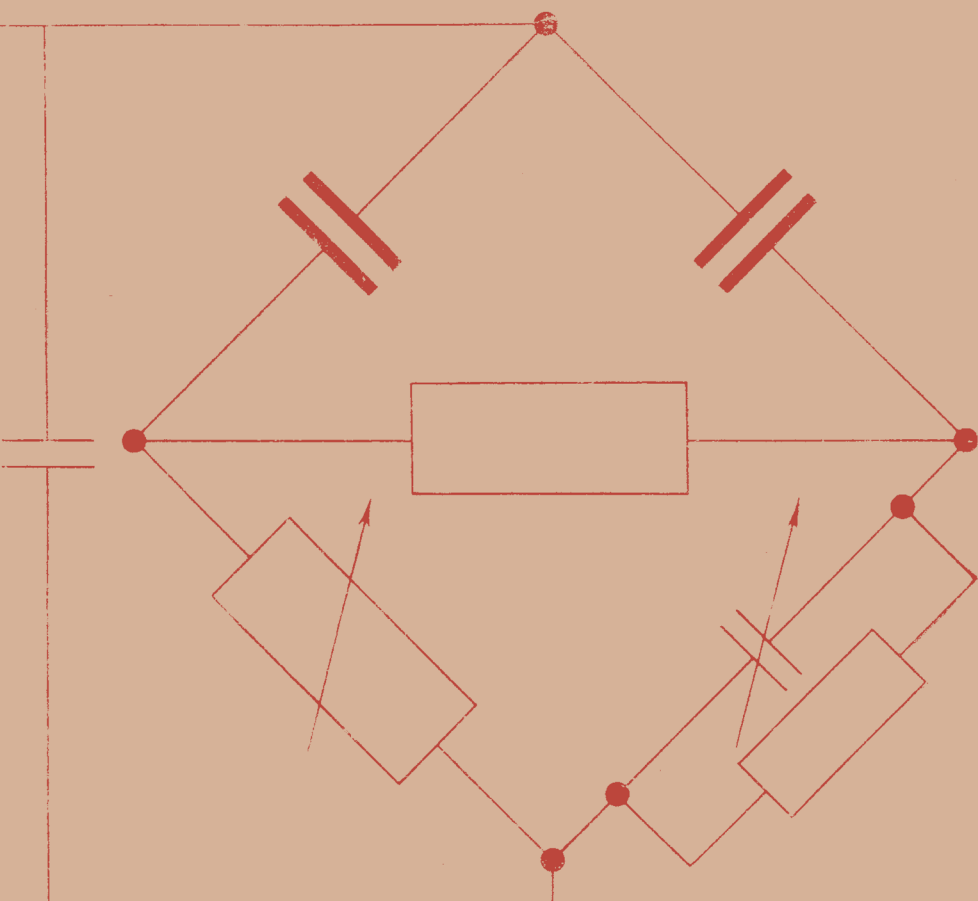
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TESTING OF ELECTRICAL INSULATING MATERIALS



MIR PUBLISHERS, MOSCOW

The textbook describes the modern methods for determining electrical and nonelectrical characteristics of electrical insulating materials and insulation systems. The chapters present information on specimens for materials and insulation components and preparation of the specimens for testing. The topics also include widespread measuring devices and test units.

The book is intended for students of secondary technical schools and may also serve as a manual for specialists engaged in testing of electrical insulating material and insulation products.

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**ИСПЫТАНИЕ
ЭЛЕКТРОИЗОЛЯЦИОННЫХ
МАТЕРИАЛОВ
И ИЗДЕЛИЙ**

Издательство «Энергия»
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The Russian Alphabet and Transliteration

А а	a	К к	k	Х х	kh
Б б	b	Л л	l	Ц ц	ts
В в	v	М м	m	Ч ч	ch
Г г	g	Н н	n	Ш ш	sh
Д д	d	О о	o	Щ щ	shch
Е е	e	П п	p	Ъ ъ	"
Ё ё	e	Р р	r	Ы ы	y
Ж ж	zh	С с	s	Ь ь	'
З з	z	Т т	t	Э э	e
И и	i	У у	u	Ю ю	yu
Й й	y	Ф ф	f	Я я	ya

The Greek Alphabet

Α α	Alpha	Ι ι	Iota	Ρ ρ	Rho
Β β	Beta	Κ κ	Kappa	Σ σ	Sigma
Γ γ	Gamma	Λ λ	Lambda	Τ τ	Tau
Δ δ	Delta	Μ μ	Mu	Υ υ	Upsilon
Ε ε	Epsilon	Ν ν	Nu	Φ φ	Phi
Ζ ζ	Zeta	Ξ ξ	Xi	Χ χ	Chi
Η η	Eta	Ο ο	Omicron	Ψ ψ	Psi
Θ θ ϑ	Theta	Π π	Pi	Ω ω	Omega

На английском языке

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PREFACE

The present text book for students of secondary technical schools is based on the third Russian edition issued in 1980. During the eleven years which have passed since the publication of the second edition substantial progress in electrical engineering has taken place; this period has seen further improvements in the quality of electrical insulating materials, elaboration of measuring and testing equipment, and standardization of testing techniques. Consequently, considerable revision of the subject matter has been necessary to bring the text up to date. Preparing the book for the third edition, we have revised all chapters, included new information, and omitted several sections which, though being of interest to specialists, do not directly relate to the course in Electrical Insulating Materials.

Unfortunately, the text was prepared without participation of professor D. M. Kazarnovsky, who untimely deceased in 1976. The contributors to the present book I. D. Forsilova, Cand. Sc. (Tech.) and L. I. Lyubimov, Cand. Sc. (Tech.), revised the chapters on electrical testing of materials and also wrote several new sections.

The exposition of the text and the subject matter conform to the requirements of the course in Electrical Insulating Materials, as adopted in 1974 by the Personnel and Training Administration of the Electrical Engineering Ministry. The authors also hope that the theoretical aspects and test methods treated in the book may be useful to specialists engaged in testing insulating materials and insulation products.

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INTRODUCTION

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The modern power industry uses a great variety of electrical insulating materials and insulation products. With the advancement of science and industry, the requirements on electrical insulation expand and become more and more complex. In this connection, testing of electrical insulation plays an increasingly important part since the main task of tests is to prove whether the properties of a particular material suit the requirements of the standards or specifications.

Prior to testing, the prepared test pieces are preconditioned and conditioned. Testing involves a number of tasks.

(1) Measuring electrical and nonelectric quantities which characterize the basic properties of an insulating material or insulation component.

(2) Establishing experimentally the relationships characterizing changes in the properties of a material due to:

(a) electrical influences (the intensity and kind of an electric field, frequency, etc.);

(b) environmental influences (temperature, pressure, humidity, mold, etc.);

(c) mechanical influences (acceleration, vibration, tension, etc.);

(d) physicochemical influences (irradiation, corrosive media, etc.);

(e) period of operation under certain conditions.

(3) Determining deviations in the properties of a material or component tested under limiting conditions simulating the possible variations of working conditions (operating temperature range, running cycles, mechanical loads or a combination of various influences).

(4) Detecting external and internal defects, the presence of impurities, admixtures or inclusions, and ascertaining structural changes.

Along with the above test procedures, additional studies on the properties of an insulating material are sometimes made; such studies may prove essential when, say, choosing the composition of a material intended to serve a specific purpose.

The amount of observations being made and the choice of test methods and equipment used may differ in each concrete case and depend on the purpose of testing. Tests of raw materials are conducted with the view to ascertain the possibility of using the supplied material (or semifinished item) for the given production process directly or after introducing certain alterations in the technological operations. These tests often help verify the quality of the raw or semifinished material and thus define the most effective range of uses for every grade. The aim of tests carried out after each successive stage of the production process is to check the semifinished product at the given production stage and determine its fitness for use at the next stage. In these tests, it is common to determine deviation of the values of quantities from the values specified in the given working instructions rather than measure the quantities themselves which define the properties of the material.

Tests performed by the manufacturer on finished products are divided into type, periodic, and approval tests.

Type tests serve to verify the compliance of an insulating material or insulation component with all the requirements of the standard or specifications. This kind of testing is conducted after elaborating a new process of production of materials or components, making modifications in the production process or converting the plant to use other raw materials. The test results enable the manufacturer to determine the characteristics of a material both in the normal and in the marginal conditions of operation. The above characteristics are also ascertained after exposing the specimens to a humid atmosphere, low temperatures, thermal cycling, and to other factors specified in the standard, which also prescribes a definite sequence and time of action of the factors. Type testing often provides an evaluation of the stab-

ility of a material (changes in its properties) after exposure to various influences, for example, after aging. Since the number of specimens subject to type tests is of prime importance, standards or specifications stipulate the required figure.

Periodic tests are conducted during the production cycle, the object of testing being to control the compliance of the finished products with the requirements of the standard, timely detect an impairment in the quality of a product and correct the trouble. The amount of periodic testing is smaller than that of type testing. This makes it all the more important to choose the right parameters for checking. Periodic tests are commonly run every 6 months. This time period may be shorter for some characteristics. Thus, the volume resistivity of certain grades of pertinax is checked not rarer than one time a month after holding the specimens in a moisture-resistance test chamber.

Approval tests are carried out by the supplier before shipping the finished products to the customer. These tests are intended to determine whether the products comply with most important requirements of the standard. Testing usually involves checks under normal conditions, but, if necessary, the properties can be verified after exposing the specimens to heat and moisture, subjecting them to mechanical loads, etc. These tests are performed for every batch of a material on a certain number of test pieces taken from the batch. Thus, the approval tests of pertinax include checks on the dimensions and external appearance of test pieces and measurements of $\tan \delta$ and E_{br} in the directions both parallel and perpendicular to the layers of pertinax.

Proof tests are often made at plants which use insulating materials and insulation components for the production of various pieces of electrical equipment. These tests are also performed at research organizations and in laboratories when evolving new designs of machines and devices. Besides, service and maintenance organizations make proof tests, too, on the supplier's materials used for the insulation of equipment (for example, tests on a new grade of transformer oil at a substation).

Preventive tests are service tests run in operating conditions. The aim of the tests is to find out whether the insulating material or insulation component still retains its proper-

ties and is serviceable enough. These tests are in the main divided into check, maintenance, and emergency types.

Check tests are checkups on materials and equipment, which prove necessary, for example, after replacement of a material or component, prolonged laying-up or storage, before starting high-voltage devices or putting into operation any piece of equipment which have been idle for some time, etc. The tests are done in accordance with working instructions.

Maintenance tests are periodic, scheduled tests intended to determine the fitness of a material (such as transformer oil) or insulation component for further service. These tests are also aimed at detecting defects in electrical insulating components, for example, in individual insulator pieces (or links) of the insulator string.

Emergency tests help study the causes that disturb the normal operation of a system, for example, clear out the origin of injury to the insulation, locate the defect, estimate the degree of serviceability of the insulation, etc.

Tests on electrical insulating materials are classified in electrical and nonelectric groups.

Electrical tests mainly serve to estimate the volume resistivity ρ_v , surface resistivity ρ_s , permittivity ϵ , loss tangent $\tan \delta$, and breakdown strength E_{br} (dielectric or electric strength) of electrical insulating materials. Apart from the above characteristics, it often becomes essential to evaluate specific electrical parameters, such as the internal resistance of anisotropic materials.

Electrical tests are made on samples or specimens of materials. It is of importance that the test results should be within the limits of error. The permissible error is stipulated in the standards and test specifications on the material. Where use is made of special test units, the accuracy of measurement is guaranteed by the producer. Such units as well as measuring devices are periodically put to state calibration testing.

Nonelectric tests are intended for determining mechanical characteristics (strength, hardness, flexibility, elasticity), physical characteristics (density, viscosity), chemical characteristics (such as oil acidity), thermal characteristics (thermal conductivity, thermal endurance, cold endurance),

characteristics associated with the effects of moisture (hygroscopicity, solubility, moisture permeability), and others.

Nonelectric test methods which estimate the structure, macrodefects, and microdefects of materials form a separate group of test methods. Here belong ultrasonic methods, X-ray and gamma-ray fluorimetric analysis, infrared spectroscopy, electron microscopy, nuclear magnetic resonance, electron paramagnetic resonance, neutron diffraction analysis, and other techniques.

Nonelectric test methods must be reliable enough to offer the estimation of corresponding parameters and characteristics to a high accuracy stipulated in the pertinent standards or specifications. Test devices and units are subject to periodic state calibration.

Preconditioning and conditioning of specimens prior to testing. Test specimens are held for some time under specified conditions prior to test. This preparation of a specimen pursues a dual purpose; first, it eliminates the effects the environment has exerted on the specimen, and, second, stabilizes the material properties, allowing the specimen to approach the test conditions. The preparation procedure consists in preconditioning and conditioning.

Preconditioning, or preliminary conditioning, is holding of specimens for a certain time period under definite conditions of the environment in order to eliminate or partially reduce the influences the material has been exposed to prior to testing. If the standard for a material does not specify the particulars of preconditioning, then the procedure comes to holding the specimen for 24 h at 50°C in the atmosphere with a relative humidity not above 20%.

Conditioning is the next stage of holding the specimens in the definite conditions of the environment for a specified period of time in order to stabilize the material properties.

In some cases it is enough to subject the test specimens only to conditioning.

The procedures of testing, preconditioning, and conditioning are prescribed in pertinent standards which also specify various combinations of temperature and relative humidity of air (Table 0.1).

In some standards, the atmosphere with a certain combi-

TABLE 0.1

**Procedures of Testing, Preconditioning, and Conditioning
(by State Standard GOST 6433.1-71)**

Medium	Temperature, °C		Relative humidity, %	
	nominal	deviation limit	nominal	deviation limit
A. Air				
Room	15-35	—	45-75	—
Medium A	20		65	
Medium B	23		50	±15
Medium C	27		65	
Humid, at normal temperature	0	±2	95	
Humid, at increased temperature	40		95	±2
Dry, at room temperature	15-35	—	20	—
Dry, at increased temperature	50, 70, 90			
	105, 120, 130	±2		
	155, 180			
	200, 220, 250	±3	20	
	275, 320, 400	±5		—
	500, 630	±10		
Cold	800, 1 000	±20	—	
	—10, —25			
	—40, —55	±2	—	—
	—60, —65			
B. Liquid				
Liquid	20, 23, 27, 50			
	70, 90, 100	±2	—	—
	105, 120, 130			

nation of temperature and relative humidity is referred to as standard atmosphere.

Preconditioning and conditioning may take from 1 hour to 16 weeks, the period being specified by the standard on a material or component. In a number of cases, conditioning involves holding the specimens in a liquid medium, though this is not the case for preconditioning. If the standard for a material does not define test conditions, the specimens are conditioned at room temperature and normal relative humidity.

In preconditioning and conditioning of specimens, one must see that the medium has free access to the specimens; the latter must not come in contact with each other and with the test chamber walls. If the specimens conditioned in a liquid medium are to be tested in the air, the residues of liquid shall be removed from the specimens with filter paper or cloth. If the procedure of testing differs from that of conditioning, the test on the specimen should begin not earlier than 5 min after its removal from the conditioning medium, if not otherwise specified. Where the temperature of conditioning differs from that of testing, the specimen should be allowed to approach the test temperature and be kept at that temperature for a certain time. The standards on materials and components prescribe how the temperature should be varied (smoothly or stepwise) to make it approach the test temperature and also specify the time of holding the specimens at the given temperature.

Using the conversion factors and the known relationships, one can reduce the test results obtained under various conditions to the conditions of the standard medium whose parameters are as follows: the temperature is 273.15 K (20°C), relative air humidity 65%, and atmospheric pressure 101.325 kPa (760 mm Hg).

In use is the standard notation which denotes in sequence the parameters of preconditioning, conditioning, and testing. In this notation the plus sign stands between the parameters of preconditioning and conditioning and the semicolon between the parameters of conditioning and testing. The letter M designates testing. Thus the notation 18 h (50) < 20 + 24 h (20) 65; M (20) 65 reads: preconditioning of a specimen for 18 h at 50°C in a dry medium (at a humidity

below 20%), then conditioning for 24 h at a temperature of 20°C and relative air humidity of 65%, and testing under the same conditions. If specimens are not subject to preconditioning and conditioning, the notation includes the letter P placed in front of M.

Statistical processing of test data. The processes occurring in electrical insulating materials, in particular the processes of failure and electrical breakdown, obey statistical laws; the measured quantity for one and the same material may vary substantially in the identical test conditions. Consider, for instance, the way of estimating the dielectric strength of materials. In testing solid materials for dielectric strength, a specimen becomes useless after its puncture so that a new specimen is necessary for the next estimation of E_{br} . In testing gaseous and liquid substances, it is possible to produce a number of repetitive punctures in one and the same sample (after cleaning periodically the electrodes, if necessary) since, after the subsequent flashover and deenergizing, the sample restores its flashover strength (in testing liquid dielectrics, one must also remove soot formed between the electrodes).

To obtain statistically reliable results in the case of a rather large scatter in test data, the same material is subjected to a number of repetitive tests (sometimes to tens of tests). In this discussion, we shall call a value found in one test an observation to distinguish it from the measurement result obtained after handling a group of observations.

Let n breakdowns have occurred under the same conditions, the recorded breakdown voltages being $U_1, U_2, \dots, U_i, \dots, U_n$. We take the result of measurement as the arithmetic mean of the number of observations

$$\bar{U} = \frac{1}{n} \sum_{i=1}^n U_i \quad (0.1)$$

where n is the number of observations.

The scatter in the individual observations of breakdown voltage U_i about the mean value \bar{U} is characterized by the standard (root-mean square) deviation, or error, σ . A limited number of observations commonly permit us to obtain

only a standard error estimate S :

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (U_i - \bar{U})^2} \quad (0.2)$$

The measurement result found from the limited number of observations will have a random error, so that its value may vary within certain limits with each group of observations. This variation is described by the standard error of the arithmetic mean or by its estimate $S_{\bar{U}}$:

$$S_{\bar{U}} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^n (U_i - \bar{U})^2} = \frac{S}{\sqrt{n}} \quad (0.3)$$

Where the spread of individual observations is large, the geometric mean of a number of observations is taken as the measurement result. This approach is resorted to in measuring, for example, the resistance of materials

$$\bar{R} = \sqrt[n]{n R_i} \quad (0.4)$$

where \bar{R} is the measurement result, that is, the geometric mean; R_i is an individual observation; and n is the number of observations. To simplify the calculations, the geometric mean is commonly found as the antilog mean of individual observations

$$\bar{R} = 10^{\frac{\sum_{i=1}^n \log R_i}{n}} \quad (0.5)$$

Obviously, we can equally well use the natural logarithms instead of the common logarithms given in the above formula.

The probability of obtaining the same value of observation under invariable test conditions in the multiple testing of the lot of specimens is determined by plotting a density curve and a distribution curve. Consider an example of the probability of dielectric breakdown for constructing these curves.

Let all the possible values of breakdown voltage lie in a definite range. Divide this range into small intervals ΔU of the same size and find the number of breakdowns in

each interval. The first interval will include n_1 breakdowns, the second n_2 breakdowns, the k -th interval n_k breakdowns, and so forth. The mean breakdown voltage in the k -th interval is U_k . Let the number of such intervals be equal to m ; it is obvious that $m < n$. The sum of all the values of n_k must be equal to the total number of breakdowns:

$$\sum_{k=1}^m n_k = n \quad (0.6)$$

Where the number of breakdowns is large, it is enough to choose an approximate mean value (a statistical average) of breakdown voltage, \bar{U}_{st} , instead of the mean breakdown voltage for all n breakdowns, the estimation of which involves difficulties. The statistical mean of breakdown voltage is evaluated in the following manner. For each interval k of voltages, we find the product $p_k U_k$, where $p_k = (n_k/n)100$. The sum of these products, divided by 100, gives the value of \bar{U}_{st} :

$$\bar{U}_{st} = \frac{1}{100} \sum_{k=1}^m p_k U_k \quad (0.7)$$

This value is close to \bar{U} in magnitude, but is not equal to the latter because we have averaged the values of voltage within each interval. For sufficiently small intervals

$$\bar{U}_{st} \approx \bar{U}$$

The probability p_k that a breakdown will occur at a voltage corresponding to the k -th interval is found (in percent) by the ratio

$$\frac{n_k}{n} 100 = p_k \quad (0.8)$$

We can plot a stepwise graph $p(U)$ which shows how p varies with U . The sum of all the values of p_k

$$\sum_{k=1}^m p_k = \frac{100}{n} \sum_{k=1}^m n_k = \frac{100}{n} n = 100$$

Plotting p as ordinates and breakdown voltages in each interval as abscissas, we obtain a stepwise graph (Fig. 0.1), called a bar chart, or histogram. The smooth curve drawn through the midpoints of the graph represents the density function.

Note that with an increase in the number of observations the function $p(U)$ approaches a smooth curve symmetric about the central ordinate. The equation for such a curve (for the process of breakdown of homogeneous dielectrics) takes the form

$$p(U) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(U_i - \bar{U})^2}{2\sigma^2}}$$

This curve describes what is called normal distribution law (the Gauss law).

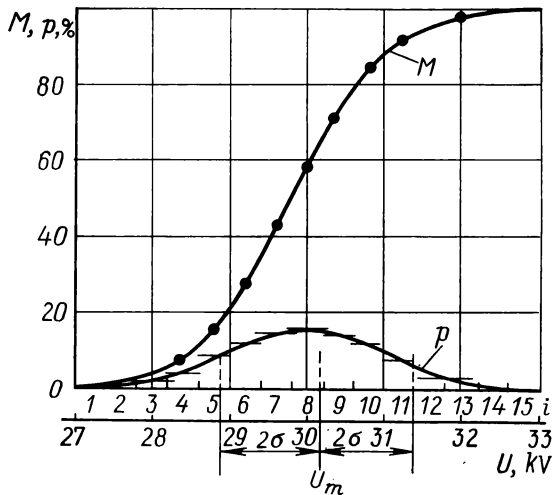


FIG. 0.1. Density distribution curve p and cumulative distribution curve M

To plot the distribution curve, we find the number of breakdowns, n_k (in percent of the total number of breakdowns n), for each interval k , that is, the number of specimens ruptured at voltage U_k and at lower values of the voltage. The increasing function $M(U)$ bears the name of the distribution function (curve M in Fig. 0.1).

The density function and the distribution function play an important part not only in determining the dielectric

strength but also in estimating other properties of electrical insulating materials when it is necessary to resort to the statistical method of handling the data of numerous observations.

Confidence interval. The probability that the absolute deviation of a certain quantity (U_k) from the mean value of this quantity (\bar{U})

$$|U_k - \bar{U}|$$

does not exceed a certain value u is expressed by Laplace's function

$$\Phi(z) = \Phi\left(\frac{u}{\sigma\sqrt{2}}\right)$$

where σ is the standard deviation. This function represents a definite integral of the form

$$\Phi(z) = \frac{2}{\pi} \int_0^z e^{-t^2} dt \quad (0.9)$$

Its values are given in the form of tables in the books on the theory of probability.

Of much interest are the values of probability of deviation for some particular cases:

1. $u = \sigma$. The probable deviation at $|U_k - \bar{U}| \leq \sigma$ is

$$\Phi\left(\frac{\sigma}{\sigma\sqrt{2}}\right) = 0.680 \quad (0.10)$$

2. $u = 1.5\sigma$. The probable deviation at $|U_k - \bar{U}| \leq 1.5\sigma$ comes to

$$\Phi\left(\frac{1.5\sigma}{\sigma\sqrt{2}}\right) = 0.866 \quad (0.11)$$

3. $u = 2\sigma$. The probable deviation at $|U_k - \bar{U}| \leq 2\sigma$ is

$$\Phi\left(\frac{2\sigma}{\sigma\sqrt{2}}\right) = 0.954 \quad (0.12)$$

In other words, if we lay off $|2\sigma|$ to the left and the right of U_m on the bar chart (curve p , Fig. 0.1), the number of breakdowns in this interval will exceed 95% of the total number of breakdowns.

The probability of deviation of a quantity from the mean value is of much interest for assessing the limits of possible

variations of the measured quantity, for example, the loss tangent δ of a dielectric. A probable deviation of 87% (at $u = 1.5 \sigma$) may often suffice, assuming that the values of $\tan \delta$ which lie beyond the limits of this interval appear only in rare, particular cases.

The bounds so established, which answer to the preset probability of deviation, specify the *confidence interval*.

The coefficient of variation. Electrical insulating materials show a certain degree of structure inhomogeneity. This feature makes itself felt, for instance, in measuring the dielectric strength of materials. If the materials are tested with the same electrodes spaced at an invariable distance, then the degree of homogeneity may be defined (providing the number of breakdowns is large) by the ratio of the standard deviation σ to the mean breakdown voltage $\bar{U} \approx \bar{U}_{st}$. This ratio is known as the coefficient of variation expressed in percent:

$$k_{var} = \frac{\sigma}{\bar{U}} 100 = 100 \sqrt{\frac{\sum_{i=1}^n (U_i - \bar{U})^2}{\bar{U}^2 (n-1)}} \quad (0.13)$$

According to the coefficient of variation in dielectric strength, electrical insulating materials are classified into more homogeneous materials with $k_{var} \leq 15\%$ and less homogeneous materials with $k_{var} > 15\%$.

Threshold breakdown voltage. The estimate of the lowest breakdown voltage at which (as with higher voltages) a considerable number of specimens rupture (or a large number of breakdowns take place) is of much importance in designing and calculating electrical insulation components. Obviously, in repetitive tests there always occur singular breakdowns at a certain minimum value of $U_{br \min}$; the probability of occurrence of such breakdowns is negligibly small so that it is hardly justifiable to take $U_{br \min}$ as a criterion for the estimation of the dielectric strength of a material.

A more well-founded approach to the estimate of dielectric strength is the method based on the reasonable, minimum admissible (threshold) probability of breakdown, M_{th} , equal to, say, 5-10%. The breakdown voltage U_{th} at which (as with lower voltages) M_{th} percent of specimens of the total number will rupture is called the threshold breakdown volt-

age at the preset minimum admissible probability. It is easy to see that

$$U_{\min} < U_{th} < \bar{U}$$

To determine the threshold voltage U_{th} , we lay off the value of cumulative probability, M_{th} , on the vertical axis M and, drawing the horizontal line until it intersects the distribution curve, find the value of U_{th} .

Consider a numerical example of the technique of statistical handling of test data. The test on a material for its dielectric strength has revealed that U_{br} lies within 27 to 33 kV. We can divide the test voltage range into equal intervals of 0.4 kV, thereby obtaining 15 such intervals; the probability p of the number of breakdowns in individual intervals turns out to vary from 0.3 to 16% (Table 0.2). These data have been used to plot the density curve (see Fig. 0.1) which closely approximates the normal distribution curve. Adding the value of p_b for a given interval k to the values of p in the preceding intervals gives the values of M , which have been plotted on the graph to produce the distribution curve M shown in Fig. 0.1. Let M_{th} be equal to 5%. Plotting this value on the M axis and drawing the horizontal line until it intersects the distribution curve, we find $U_{th} = 28.2$ kV.

It should be interesting to note that in the given case the statistical average of breakdown voltage is $\bar{U}_{st} = 30.24$ kV, the standard deviation $\sigma = 0.676$ kV, and the coefficient of variation, $k_{var} = 2.24\%$.

So, the material subjected to the test belongs to the materials of the first group of structure homogeneity.

The Student criterion. To obtain a large number of points and thus construct a distribution curve it is necessary to make numerous measurements on many specimens. For this reason, it often proves expedient to limit oneself to a small number of observations (specimens), striving to find a representative value of the characteristic with an accuracy sufficient for practical purposes. Handling a limited number of observations (termed limited population) with the aid of the Student criterion enables us to set up to a certain degree of probability the bounds within which lies the mean

TABLE 0.2

An Example of Statistical Processing of Dielectric Strength Measurement Results

Quantity	Interval number														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
<i>Experimental data</i>															
Voltage U_i , kV	27.2	27.6	28.0	28.4	28.8	29.2	29.6	30.0	30.4	30.8	31.2	31.6	32.0	32.4	32.8
Number of breakdowns, p , % . . .	0.3	1.0	2.0	4.0	8.5	12.0	14.5	16.0	14.0	12.0	8.0	3.0	3.0	1.0	0.7
<i>Calculated data</i>															
Total number of breakdowns, M , %	0.3	1.3	3.3	7.3	15.8	27.8	42.3	58.3	72.3	84.3	92.3	95.3	98.3	99.3	100
$ U_i - \bar{U} $	3.04	2.64	2.24	1.84	1.44	1.04	0.64	0.24	0.16	0.56	0.96	1.36	1.76	2.16	2.56
$\langle U_i - \bar{U} \rangle^2$	9.25	6.97	5.00	3.38	2.07	1.08	0.41	0.06	0.013	0.31	0.92	1.85	3.04	4.67	6.55

$$\bar{U} = 30.24 \text{ kV}; \quad \Sigma p_h = 100\%; \quad \frac{\Sigma (U_i - \bar{U})^2}{n-1} = 0.456 \text{ kV}^2; \quad \sigma = 0.676 \text{ kV}; \quad k_{\text{var}} = \frac{\sigma}{\bar{U}} 100 = 2.24\%.$$

value of the sought-for quantity that conforms to the total population, that is, to a sufficiently large number of tests.

Consider the sequence of statistical handling of observation results, for example, the data on permittivity ε .

Find the mean value of the limited population:

$$\bar{\varepsilon} = \frac{1}{n} \sum_{i=1}^n \varepsilon_i$$

where n is the number of observations. Instead of determining the standard deviation σ , which is unknown for the limited population, we estimate this deviation by the formula

$$S = \sqrt{\frac{\sum_{i=1}^n (\varepsilon_i - \bar{\varepsilon})^2}{n-1}}$$

According to the Student criterion, the bounds within which lies the mean value of total population, ε , are determined by the quantities

$$\bar{\varepsilon} \pm \frac{S}{\sqrt{n}} t(\gamma)$$

They are often called confidence, or fiducial, limits at the fiducial probability γ . Here $t(\gamma)$ is the tabulated function (Table 0.3) of the probability γ and the number of observations. n . The fiducial probability is commonly taken to equal 0.950-0.999. The greater the number of observations, the closer the bounds lie to each other, that is, the more accurate is the estimate of $\bar{\varepsilon}$.

Presentation of test results. The observation results are entered in the test data log which must be kept in the laboratory or at the test station. Besides, a test record sheet is made up, which contains both general and special data.

General data include:

(a) description of a material, namely, its name, grade, color, application, producer, etc.;

(b) date of delivery and testing;

(c) schedule of preconditioning and conditioning of specimens, that is, the conditions of storing prior to testing, preliminary drying, time t of holding in the atmosphere at a certain relative humidity and temperature T , etc.;

TABLE 0.3

Student Criterion, Function $t_0(\gamma)$

$n-1$	Fiducial probability γ			
	0.950	0.980	0.990	0.999
4	2.78	3.75	4.60	8.61
5	2.57	3.37	4.03	6.87
6	2.45	3.14	3.71	5.96
7	2.37	3.00	3.50	5.41
8	2.31	2.90	3.36	5.04
9	2.26	2.82	3.25	4.78
14	2.15	2.62	2.98	4.14
19	2.09	2.54	2.86	3.88
24	2.06	2.49	2.80	3.75
29	2.05	2.46	2.76	3.66
40	2.02	2.42	2.70	3.55
50	2.01	2.40	2.68	3.50
60	2.00	2.39	2.66	3.46
80	1.99	2.37	2.64	3.42

(d) description of specimens and electrodes used in testing, that is, the shape and dimensions of specimens, type and dimensions of electrodes, electrode materials and electrode coatings, etc.;

(e) test conditions, that is, the temperature of a specimen or liquid sample, relative air humidity, test duration, etc.;

(f) data on measuring devices, indication of their accuracy classes and description of the test unit.

Special data have to do with the purpose and method of testing and also with the characteristic features of the material being tested. The record sheet is signed by the supervisor and the personnel directly engaged in testing.

ELECTRIC RESISTANCE OF INSULATING MATERIALS

1.1. General

Electrical insulating materials display the property of electric conduction under applied voltage. Though the conductance of these materials is many orders of magnitude smaller than that of semiconductors, let alone the conductors proper, this characteristic is of great practical importance.

If we apply a d.c. voltage to the electrodes of a specimen, a leakage (conduction) current will flow through the specimen. This current consists of two components. One is the current that passes through a thin current-conductive layer of moisture containing dissolved substances; this layer forms as a result of precipitation of moisture from the air on to the specimen surface. The first current component is known as the surface leakage current. The second component is the current flowing through the insulating material proper, that is, through the bulk of the insulation specimen. This is the bulk (volume) leakage current. So, the equivalent circuit of the test specimen should consist of two resistances connected in parallel. The first, R_s , takes into account the surface current of the dielectric, and, the second, R_v , the volume current. It is commonly desirable to measure each component separately, eliminating the influence of the other component. For this purpose, measurement methods use electrode arrangements consisting of three electrodes: a guard electrode, guarded (measuring) electrode, and unguarded (high-voltage, or just high) electrode. For example, in a three-electrode system, shown in Fig. 1.1a, for measuring the volume resistance R_v of a flat specimen 3, a guard electrode 2 has the shape of a ring kept in a position concentric with a guarded electrode 1 on one of the faces of the specimen. An unguarded electrode 4 is disposed on the opposite face of the specimen. The guard electrode effectively

equalizes the field between the guarded and the unguarded electrode and drains into the earth the surface and volume currents in the edge regions of the specimen, with the result that these currents have no effect on the readings taken from the instrument. Guard electrodes also find use for tubular

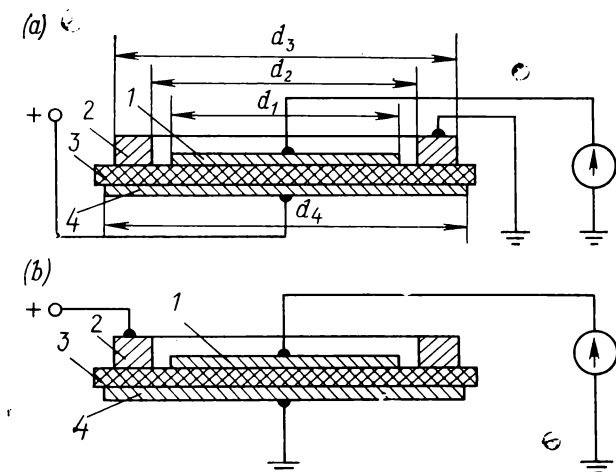


FIG. 1.1. Three-electrode system for a flat specimen

specimens, the arrangement being similar to the one described.

In measuring the surface resistance R_s of a flat specimen, the electrode 1 performs the same function as in the above arrangement, while the ring electrode 2 serves as a high-voltage electrode. The guard electrode 4 has the shape of a disc disposed on the opposite face of the specimen 3 (Fig. 1.1b); the electrode dissipates the bulk current into the earth, so that this current has no bearing on the indication of the measuring device.

Proof test methods often employ a simpler, two-electrode system.

Volume and surface resistances depend not only on the material of a specimen but also on the specimen's geometric dimensions. To determine the degree to which various materials differ in conduction, one uses the notion of the volume

resistivity ρ_v and the surface resistivity ρ_s of a dielectric.

Volume resistivity. This quantity is defined as the ratio of the potential gradient, that is, the electric field strength E , in a specimen to the current density J . The volume resistivity ρ_v is proportional to the volume resistance R_v . The quantity which is the reciprocal of ρ_v is known as the volume conductivity:

$$\gamma_v = 1/\rho_v \quad (1.1)$$

In measuring R_v of a flat specimen, we determine the volume resistance of the specimen portion confined between the guarded and the unguarded electrode (see Fig. 1.1a). In this case, the calculated (effective) diameter d_m is equal to the arithmetic mean of d_1 and d_2 :

$$d_m = \frac{d_1 + d_2}{2}$$

where d_1 is the diameter of the guarded electrode; and d_2 is the inner diameter of the ring-shaped guard electrode. The resistance R_v of the flat specimen is expressed in the form

$$R_v = \rho_v \frac{t}{\pi d_m^2/4} \quad (1.2)$$

where t is the specimen thickness.

If R is measured in ohms and t and d_m in meters, then the unit of measurement of ρ is the ohm-meter (Ω m).

From equation (1.2) we find

$$\rho_v = 0.785 R_v \frac{d_m^2}{t} \quad (1.3)$$

Surface resistivity. According to the definition given in the Soviet State Standard 21515-76, the surface resistivity is the resistance between two opposite edges of a unit square of the surface of a solid dielectric when an electric current flows between these two edges. In the simplest case (Fig. 1.2), where the electrodes are two straight conductors placed on a specimen, the surface resistance R_s is proportional to the interelectrode gap g and inversely proportional to the electrode length a :

$$R_s = \rho_s \frac{g}{a} \quad (1.4)$$

The unit of surface resistivity is the ohm (Ω).

Internal resistance. Electrical insulating materials often display anisotropy in various directions. A specimen shows a smaller resistance in the direction parallel to its surface (in laminates, along the specimen layers) than in the direc-

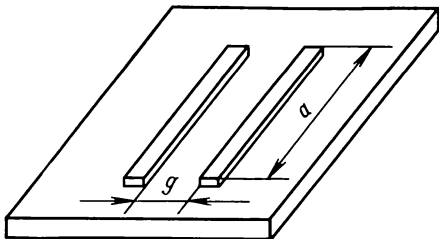


FIG. 1.2. Illustrating the calculation of surface resistance R_s of a flat specimen

tion perpendicular to its surface. It is an internal resistance R_i that may serve as a characteristic for such materials. This resistance is measured between two standard cylindrical electrodes tightly imbedded in a specimen and spaced at a certain distance (see Fig. 1.6). Apart from the internal resistance R_i , recourse is sometimes made to the notion of internal resistivity ρ_i , calculated by the formula

$$R_i = \rho_i \frac{h}{ad} \quad (1.5)$$

where h is the shortest distance between cylindrical electrodes; d is the diameter of electrodes; and a is the height of electrodes. It is clear from the above formula that ρ_i is measured in ohm-meters or ohm-centimeters.

Insulation resistance. By definition, this is the ratio between the voltage applied to a specimen and the total current flowing through the bulk of the specimen and over its surface between the two electrodes. The insulation resistance R_{ins} is thus equal to the volume resistance R_v of a dielectric and its surface resistance R_s connected in parallel.

The above relations show that in studying electric conduction in insulating materials the measurement comes to determining the resistance of specimens; depending on the system of electrodes being used, this resistance may be R_v , R_s , R_i or R_{ins} . A sought-for resistance is measured with the same methods and devices; in the further discus-

sion, the resistance of a specimen will be designated as R_x . The quantity R_x is closely related to such characteristics of materials as volume resistivity ρ_v , surface resistivity ρ_s , and, sometimes, to internal resistivity ρ_i .

The accuracy of measurement of resistances and resistivities depends on the accuracy of instruments, the choice of electrodes and their arrangement on a specimen, and the shape and dimensions of the specimen.

1.2. Specimens and Electrodes for Solid Materials

The quantities R_v , R_s , ρ_v , and ρ_s of solid electrical insulating materials (films excepted) are determined on flat specimens (discs and square plates) or tubular specimens; R_s can also be measured on test bars (Fig. 1.3). The diameter of a flat specimen (or the side of a square) can range from 25 to 150 mm, and the length of tubular specimens from 100 to 300 mm. Where use is made of a test bar piece, its length must be equal to 50-100 mm. Flat and tubular specimens (films excepted) commonly have a wall thickness of 0.5 to 2 mm. The thickness of a test specimen is found as the arithmetic mean of thicknesses measured at five points in the region of location of a guarded electrode. The thickness measurement error must be within $\pm 1\%$. The scatter in specimen thicknesses must be kept at 2% if these are larger than 0.5 mm, and at 5% for thicknesses of less than 0.5 mm. The choice of the specimen's shape and size is determined in accordance with the standard or specifications on the material under test. For anisotropic materials, the internal resistance R_i is measured on a flat specimen having two 5-mm diameter blind holes spaced 15 mm apart (Fig. 1.4). The thickness t of such a specimen must be not less than 8 mm; the hole depth H (mm) is a function of t :

$$H = t/2 + 2.5$$

The number of specimens should not be less than three.

The insulation resistance R_{ins} is determined on flat, tubular, cylindrical, and bar specimens 1 to 50 mm thick provided with two through holes for 5-mm diameter elect-

rodes (Fig. 1.5). The drilled holes are reamed at a taper of 1 : 50. The centre-to-centre distance A must be equal to 15 ± 1 mm or 25 ± 1 mm. The specimens must show no warping or spalling, be free of fissures, hollows, burrs, and

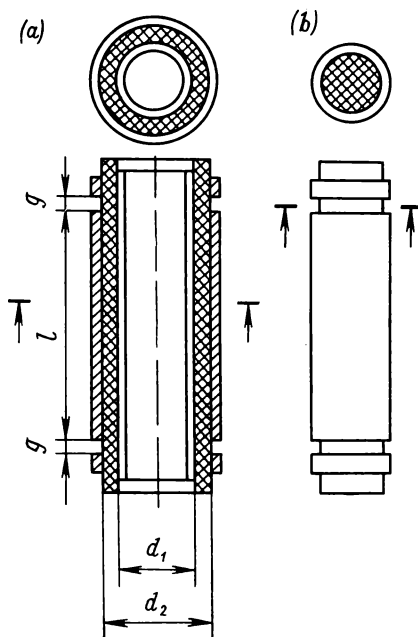


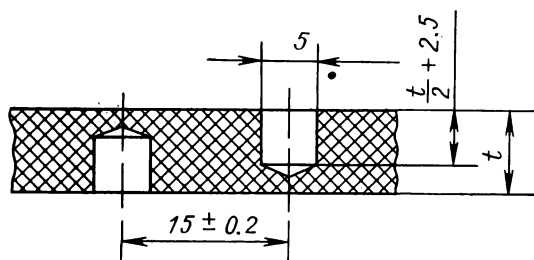
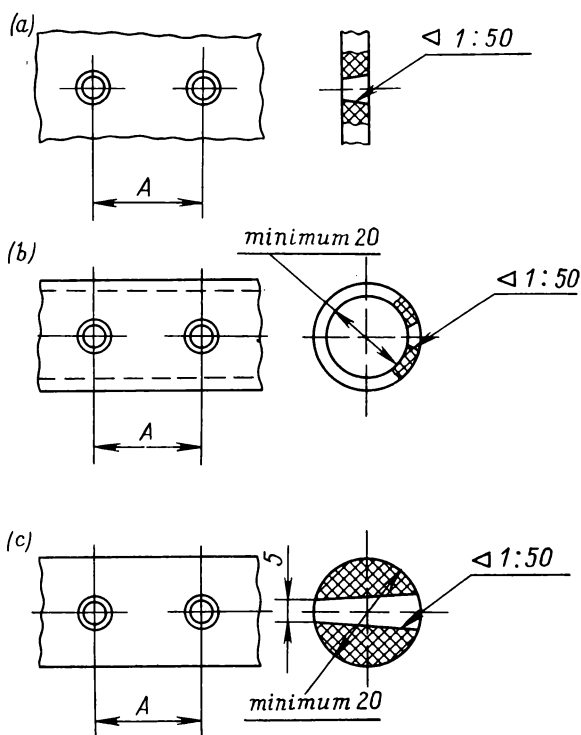
FIG. 1.3. Arrangement of electrodes on a flat specimen (a) and on a rod specimen (b)

dirt. The surface of specimens after machining must be smooth, without dents and scratches.

The electrodes for testing solid dielectrics shall satisfy the following basic requirements:

1. The electrode shall have high conductance and make good electric contact with the specimen over the entire contact surface, thereby excluding any airgap between the electrode and specimen.

2. The electrode shall not deform the test specimen, nor exert chemical or other influences during testing.

FIG. 1.4. Specimen for measuring R_i and ρ_i FIG. 1.5. Specimens for measuring R_{ins}
(a) flat; (b) tubular; (c) cylindrical

3. The electrode shall not vary in shape and size during testing, nor undergo any physical or chemical changes such as melting and oxidation.

4. The electrode shall be simple in design (to ensure ease of fabrication, for example, by deposition) and show readiness for use immediately after its application.

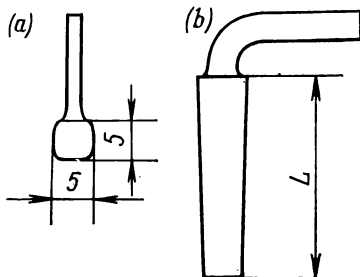


FIG. 1.6. Electrodes (a) for measuring R_i ; (b) for measuring R_{ins}

Standards specify the use of the following test electrodes: massive metallic, foil, sputted-on or fired-on (fused-on), and graphite types. Massive metallic electrodes are intended for the measurement of R_v , R_s , R_i , and R_{ins} . They are made from stainless steel, copper, and brass. The working surface of massive electrodes must be smooth. Tight contact with the material of a specimen is ensured by pressing the electrode at 10 kPa. Electrodes for internal resistance measurements have the shape of a cylinder 5 mm in diameter and 5 mm in height (Fig. 1.6a). The resistance R_{ins} is determined with cone-shaped pin electrodes with a length L from 40 to 70 mm (Fig. 1.6b). Foil electrodes are cut from annealed aluminum foil 5 to 20 μm thick. They are used for the measurement of ρ_v and ρ_s .

Foil electrodes are bonded to specimens by any of the three methods. The first involves the use of lubricants such as petrolatum, transformer oil or silicone grease to make the foil stick evenly to the specimen surface and thus provide tight electrode-to-specimen contact. The lubricant layer thickness must not exceed 1 μm . The second method, mostly applied to plastics and films, combines pressing with heating. The third method consists in pressing foil electrodes against the surface of a specimen under a pressure of 10 kPa

through a rubber spacer. Such electrodes are applicable for flat sheet materials. In these electrodes, the foil is fastened to a rubber spacer with the aid of a holder (Fig. 1.7).

Electrodes of deposited metals such as silver, gold, platinum, copper or aluminum are films tightly adhering to the surface of dielectrics. There is a number of methods for de-

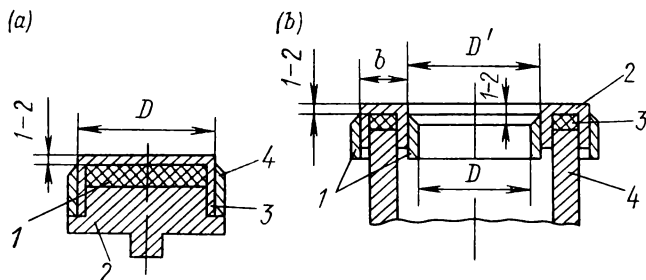


FIG. 1.7. Foil-rubber electrodes for flat specimens

(a) internal electrode; 1—rubber disc; 2—metallic holder of electrode; 3—foil; 4—metal ring
(b) external electrode; 1—metal ring; 2—foil; 3—rubber ring; 4—metallic cylinder

position of such films. The method of fusion (firing) is commonly employed for depositing silver electrodes. The silver paint used for the purpose must contain not less than 50 % silver; the paint consists of silver carbonate, a fusing agent (bismuth carbonate and others), and an organic binder (a solution of rosin in turpentine). The paint is applied with a brush to a specimen to form an electrode of the desired shape and dimensions. The painted specimen is subjected to drying and then heating (firing) in a muffle furnace. During firing the organic components burn off and silver carbonate decomposes to form a film of metallic silver strongly adhering to the specimen surface. This method of film deposition requires heating to a few hundred degrees Celsius, so that only ceramic, mica, and, partly, glass specimens can withstand such temperatures. Low-temperature silver paints are also available. The fused layer of silver must be dense and uniform, without ruptures when observing the coat with a five-power magnifier. The method of vacuum evaporation permits depositing electrodes from platinum, gold, silver, copper, and aluminum with the aid of a mask

that defines the electrode shape. These same metals can be deposited by cathode sputtering in a vacuum and also by chemical precipitation that obviates the need for producing vacuum. One must see that there is no deposited metal, reaction products or other foreign substances in the spacing between the guard and guarded electrode. The layer of de-

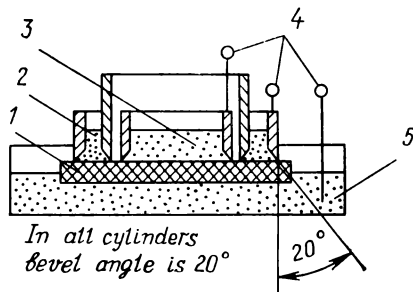


FIG. 1.8. Graphite electrodes for flat specimens

1—specimen; 2—guard electrode; 3—guarded electrode (graphite); 4—terminal; 5—high-voltage electrode (graphite)

posited metal must give a uniform coat so that no fractures and broken edges shall be visible through a five-power magnifying glass.

Graphite electrodes can mainly be made either from a liquid suspension with a varnish binder (such as an epoxy lacquer and shellac lacquer) or from the powder of natural graphite. The graphite-varnish suspension is applied to a specimen either by brushing or spraying through a stencil cut from, say, dense paper. The thickness of the deposited film shall be equal to approximately 0.1 mm. The coat shall be uniform; no ruptures or broken edges shall be visible through a five-power magniglass. The resistance of the graphite-varnish film shall be under 100 Ω . To produce electrode from powdered graphite, one can place a specimen on a graphite powder bed and then suitably arrange three concentric rings on the specimen (Fig. 1.8). Next it is necessary to pour graphite powder into the gap between the two outer rings and into the space confined within the inner ring, and then compact the powder at a pressure of 10 kPa.

Electrodes prepared from foil, silver paint, deposited metal or graphite are connected to respective terminals with

massive steel, brass or copper elements having in plan the shape and dimensions of film electrodes. It is allowable to solder wire connectors directly to fired-on silver electrodes or to sputtered-on film electrodes. As mentioned earlier, the measurements of ρ_v or ρ_s are made with a three-electrode system that consists of a guarded electrode, high-voltage electrode, and guard electrode. If volume resistivity is measured on a flat specimen, the guarded electrode made as a disc with a diameter d_1 is arranged in the center of the guard electrode having the shape of a ring with an internal diameter d_2 and external diameter d_3 . The high electrode with a diameter d_4 (see Fig. 1.1) is placed concentrically on the opposite face of the specimen. It is common to use the measuring electrode with a diameter $d_1 = 50$ mm, the high-voltage electrode with $d_4 = 75$ mm, and the guard electrode with $d_2 = 54$ mm and $d_3 = 74$ mm; electrodes of other dimensions can also be used (Table 1.1).

TABLE 1.1

Dimensions of Electrodes for Flat Specimens, mm

d_1	d_2	d_3 , not less than	d_4 , not less than
100	104	124	125
75	79	99	100
50	54	74	75
25	29	39	40
10	14	18	20

The fired-on silver electrodes for flat ceramic specimens may have the following diameters: $d_1 = 65$ mm for the guarded electrode, $d_2 = 69$ mm and $d_3 \geq 89$ mm for the guard electrode, and $d_4 = 90$ mm for the high-voltage electrode. The gap between the guard and the guarded electrode shall be equal to 2 mm.

In determining ρ_v of a varnish film deposited on a metal substrate, or ρ_v of a compound poured into a metal cup, the metal substrate or the metal cup play the part of a high-voltage electrode. For a tubular specimen, the length of a guarded electrode is 50 to 250 mm, the length of a high

electrode is 75 to 300 mm, and the width of a guard electrode is 10 mm. The gap between the guarded electrode and the guard electrodes placed on the opposite sides shall be equal to 2 mm. The same three-electrode system is used for measuring the surface resistivity ρ_s of solid materials, but in this case the guard ring must play the role of a high electrode, while the high electrode must serve as a guard electrode; this is apparent from the method of connection of the three-electrode system in the measuring circuit, as shown in Fig. 1.1. In determining R_{ins} , it is permissible to use knife or foil electrodes in the form of strips 100 mm long and 10 mm wide running parallel to one another with a gap of 10 mm inbetween. Knife electrodes 100 mm in length shall be spaced 10 mm apart (Fig. 1.9); they are fixed with screws to two metal bars insulated from each other with an airgap. On the opposite side of each bar there are two stepped holes with insulating bushes to let pass the screws for fastening the bars to the base placed on top of the electrode arrangement; the base and bars are separated from one another with an insulating spacer, or pad. The base is provided with rectangular openings for installing a measuring terminal M and high-voltage terminal H connected to the respective electrodes. The metal base is grounded. The resistivity ρ_s of a test bar is measured with a two-electrode system. The electrodes here are rings, each not less than 10 mm wide; the gap between the rings that encircle the specimen must be equal to 2 mm.

In measuring R_{ins} in the direction parallel to the surface of a specimen (for laminated materials, along the layers of a specimen), two cylindrical electrodes 5 mm in diameter and 5 mm in height are used, which are pressed tightly, well home, into blind holes drilled in the specimen (see Fig. 1.4). Instead of massive electrodes, one can use film electrodes deposited on the inside of the holes. The resistivity ρ_v of varnish or enamel films is measured on specimens having a guarded electrode with $d_1 = 50$ mm and a guard electrode with $d_2 = 54$ mm and $d_3 = 74$ mm, both being prepared from aluminum foil smoothed over and pressed to the specimen surface. The plate (substrate) for the film of varnish or enamel serves here as a high-voltage electrode.

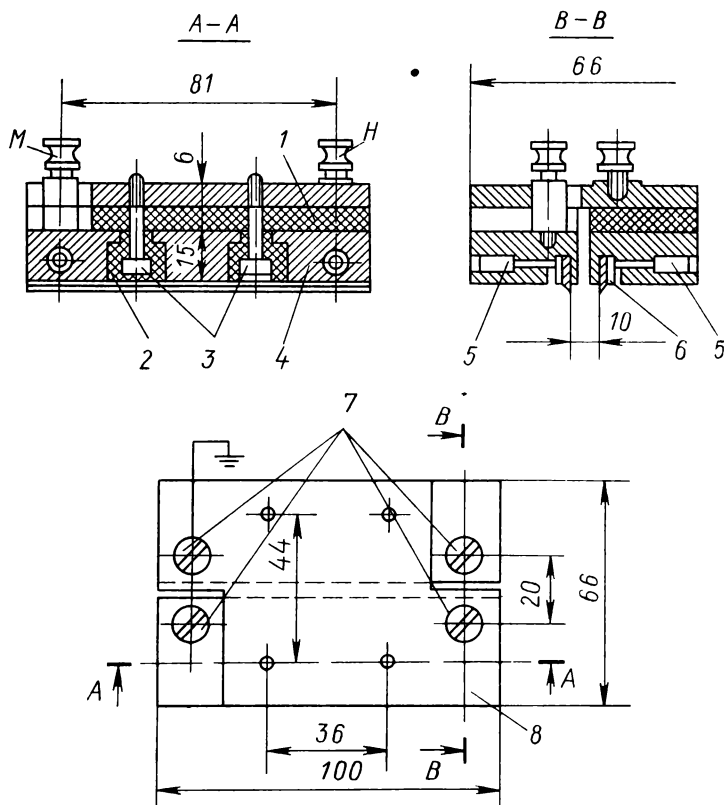


FIG. 1.9. Knife electrodes for measuring R_{ins}

1—insulating pad; 2—insulating bush; 3—screws to fasten electrode bars passing through bushes; 4—electrode bars; 5—clamping screws for knife electrodes; 6—knife electrodes; 7—terminals; 8—base

Varnish or enamel film specimens are prepared in the following manner. A substrate (a metal plate) is immersed vertically into a vessel, containing a varnish or enamel at a temperature of 20°C , with a rate of 0.35 m/min . The substrate is held in the vessel for 1 min and then taken out at the same speed. The specimen is predried at 20°C or at a higher temperature for 10 to 15 min. The plate, preliminarily inverted to make its lower edge become the upper edge, is dipped anew into the varnish and drawn off, now without

allowing it to stay in the vessel. The viscosity and concentration of the varnish or enamel are adjusted (by adding or evaporating the solvent) so that the film on either side of the substrate can be 50 μm thick, the thickness variation being set at $\pm 5 \mu\text{m}$. The film coated substrates are then dried in a vertical position either in the air or in a constant-temperature cabinet (thermostatic oven), the temperature and time of drying being specified by the standard. Substrates are made of copper or brass (0.4 to 0.6 mm in thickness), stainless steel (0.8 to 2 mm), aluminum (1 or 2 mm), and aluminum or copper foil (0.1 or 0.2 mm thick). Before applying coats on substrates, a varnish (or enamel) should be allowed to stand for some time until the varnish ceases to evolve air bubbles. Substrates should be cleaned of oxides, washed in gasoline, and dried.

1.3. Measuring Cells for Liquid Materials

A measuring cell is a special metal vessel furnished with electrodes, commonly of stainless steel, for measuring the volume resistivity ρ_v of liquid dielectrics on at least two samples, each not below 50 cm^3 in volume. The working surface of electrodes must have a smooth coat of nickel, chromium or silver. In the three-terminal design of a measuring cell complete with flat electrodes (Fig. 1.10a) the high electrode 5 has the shape of a disc with a flat bottom. The insulating element 4 prepared from fused quartz or polytetrafluoroethylene in the form of a ring bears on disc edges. The ring-shaped guard electrode 2 is fixed to this element with screws and provided with an internal circular seat for an insulating ring 3. This ring serves as a support for a central measuring electrode 1. The electrodes are provided with terminals 6 for connecting the cell to the measuring circuit.

In a measuring cell with cylindrical electrodes (Fig. 1.10b), a high electrode 5 takes the form of a deep cup whose upper portion has a circular seat for an insulating ring 4 on which rests a ring-shaped guard electrode 2. This electrode has an internal circular seat, too, to support a second insulating ring 3 which in turn gives support to a measuring electrode 6

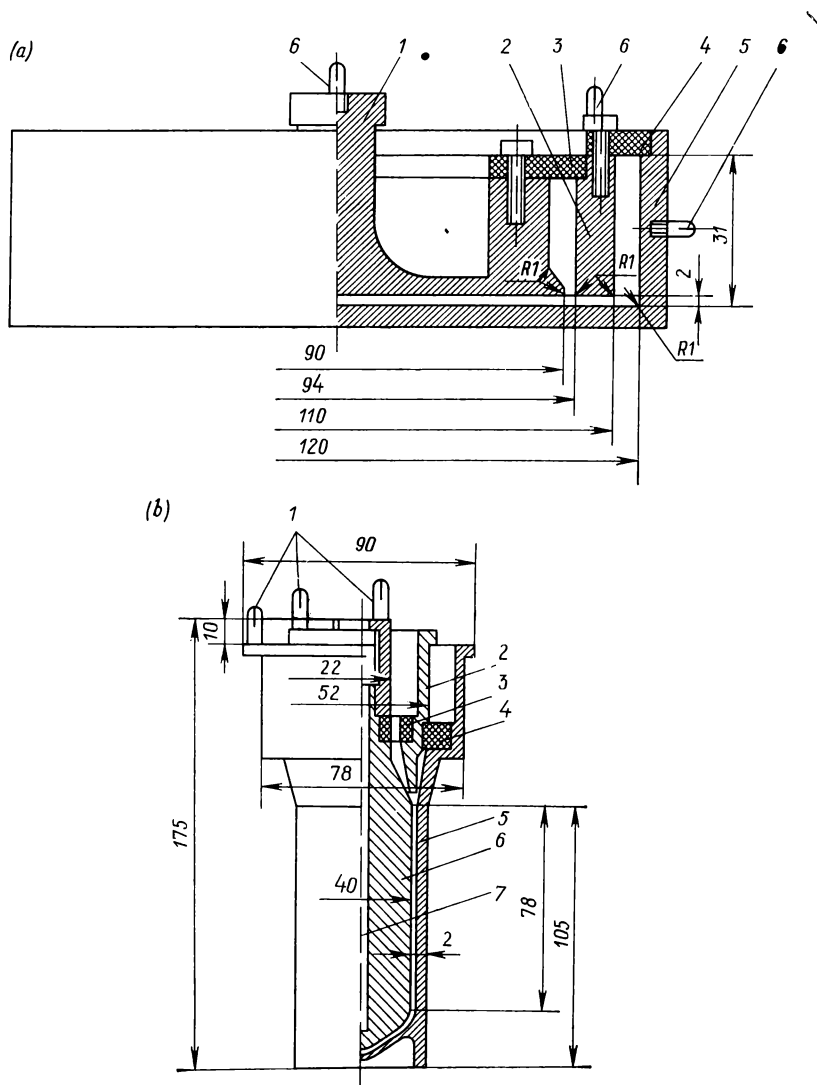


FIG. 1.10. Measuring cell for liquids
(a) flat; (b) cylindrical

made in the form of a cylinder with a cone-shaped top. The cylinder has an axial chamber 7 for housing a thermometer or thermocouple. Terminals 1 serve to connect the respective electrodes to the measuring circuit.

The basic dimensions of the described cells are given in the figure. The strictly specified dimensions in the design of a measuring cell are: the gap between the guarded and the high electrode and the gap between the guarded and the guard electrode. Each gap shall be equal to 2 ± 0.1 mm.

Prior to making measurements, the cell shall be thoroughly cleansed, first, with a solvent, then with an aqueous solution of neutral detergent, and, finally, with hot distilled water. Particular care should be taken to see that the insulating pads are sufficiently clean. The cell is dried at 105 to 110°C for 90 min. The assembled cell is then connected to the measuring circuit to check the insulating elements for cleanliness by making a set of resistance measurements on the empty cell, whose resistance shall be one or two orders of magnitude higher than that for the cell filled with a test liquid. If this requirement is not met, the cell should be disassembled and cleansed again.

1.4. Resistance and Resistivity Measurements

As shown in the preceding sections, R_v , R_s , R_i and R_{ins} can be determined by measuring the resistance between the measuring and the high electrode. This type of measurement can be carried out directly, using a suitable device of a sufficient accuracy, or indirectly, in which case it is necessary to measure the current I passing through the specimen from the high-voltage to the measuring electrode at a preset test voltage U across these electrodes. The resistance is then found by Ohm's law: $R = U/I$.

In any case, the measurement method must be accurate to within $\pm 5\%$, $\pm 10\%$ and 20% where the sought-for resistance is expected to reach $10^9 \Omega$, 10^9 to $10^{13} \Omega$, and above $10^{13} \Omega$ respectively.

Obviously, the direct measurement of resistances with, say, a megohmmeter is simpler than the indirect measurement. But it is not always possible to conduct direct measure-

ments as it may seem at first glance. The fact is that the resistance of a material depends on the value of applied voltage. In order to have the possibility of comparing the results of tests on various materials, the standard recommends the following range of test voltages: 25, 50, 100, 250, 500, 1 000, and 2 500 V. The deviation of the test voltage from the specified value shall not exceed 2% and 1.5% in testing solid dielectrics and liquid materials respectively. The instability and pulsation of the voltage impressed on a specimen shall be kept under 1%. The tests on certain materials call for smooth stepping-up of the test voltage at a predetermined rate. However, not all the direct-acting instruments (megohmmeters, teraohmmeters) do meet these requirements. That is why the resistance of a specimen is more often measured indirectly. In this case, the measuring unit must be adapted to build up specified voltages across the specimen and measure currents flowing through it. Since the voltages applied to a specimen are high, while the currents through the specimen are extremely small, one should provide for a high-quality insulation of the measuring unit. The allowable current in the measuring circuit, with the specimen disconnected and the test voltage applied, must be at least by a factor of 100 smaller than the current that appears after connection of the specimen to the circuit.

TABLE 1.2

Formulas for Calculating Resistivities ρ_v and ρ_s

Shape of specimen and electrodes	Formula
Flat specimen with ring-shaped and disc-like electrodes (Fig. 1.1)	$\rho_v = \pi \frac{(d_1 + d_2)^2}{16t} R_v, \rho_s = \pi \frac{d_1 + d_2}{2g} R_s$
Flat specimen with rectangular electrodes (Fig. 1.2)	$\rho_v = \frac{(a+g)(c+g)}{t} R_v, \rho_s = \frac{2(a+c+2g)}{g} R_s$
Tubular and cylindrical specimens (Fig. 1.3)	$\rho_v = 2.73 \frac{(l+g)}{\log(d_2/d_1)} R_v, \rho_s = 2\pi \frac{d_2}{g} R_s$

Resistivities ρ_v , ρ_s , and ρ_i are always determined by indirect measurements. For this, it is required to know the dimensions of a specimen apart from its resistance; in testing liquid materials, one should also know the capacitance of the measuring cell in a vacuum (air). The formulas for calculating surface and volume resistivities of solid specimens of various shapes appear in Table 1.2. For calculating ρ_v of a liquid material, either of the formulas given below may do well:

$$\rho_v = \frac{R_v C_0}{\epsilon_0}, \quad \rho_v = 11.3 \times 10^{10} C_0 R_v$$

where R_v is the measured volume resistance, Ω ; C_0 is the capacitance of an empty cell, F; and ϵ_0 is the electric constant, equal to 8.854×10^{-12} F/m.

ELECTRIC RESISTANCE MEASUREMENTS

2.1. General

Tests on electrical insulating materials involve measuring high resistances, up to $10^{16} \Omega$ and above, and very small currents, down to 10^{-14} A and below. This calls for special instruments and measurement methods. We have mentioned in Chapter 1 that the resistance of a specimen can be determined both directly and indirectly. Direct measurement methods use vacuum-tube and semiconductor megohmmeters (teraohmmeters). These devices measure resistances that can be read directly on the scale. The permissible error limits for megohmmeters can vary from $\pm 5\%$ to $\pm 20\%$ depending on the resistance measuring range.

In indirect measurements the resistance of a specimen is estimated either from the measured current through the specimen at the known test voltage or from the voltage drop across the specimen at the known current. The measurements of current (voltage) are made with moving-coil galvanometers, electrostatic and electronic electrometers. These devices exhibit very high sensitivity and can measure extremely small values of current down to 10^{-17} A (at this current as few as 62 electrons pass through the conductor cross section in a second). In indirect measurements, however, the measurement process itself proves more complex, takes more time and involves additional calculations. Note also that since the value of the unknown (resistance R_x) is calculated from the results of direct measurement of other quantities (current or voltage), the latter two quantities must be determined with a higher accuracy because the error of the result will be the sum of the errors of the components.

Measuring very low currents presents considerable difficulties because of the instability of readings, changes in

the ambient temperature, fluctuation noise, and other interferences. For this reason, the resistance measurement on specimens of high-quality materials makes it necessary to shield thoroughly the elements of the measuring set and ensure its steady operation by stabilizing the supply voltage and temperature. Particular attention should be focused on the quality and cleanliness of contacting elements. The set should be well grounded to exclude a hazard to the personnel as well as secure the stability of readings.

2.2. Measurements with a Moving-Coil Galvanometer

Since they show a high sensitivity, moving-coil galvanometers find wide use in tests on electrical insulating materials and components for measuring small currents. The sensitivity of a galvanometer is the ratio of its response to cause, that is, the ratio of the magnitude of instrument deflection to the magnitude of an input signal (the quantity being measured). It is usual to differentiate between the sensitivity of a galvanometer relative to current, S_I , and its sensitivity to voltage, S_V . The quantity which is the reciprocal of sensitivity is known as a galvanometer constant (deflection factor) C_I or C_V marked on the galvanometer. The current constant C_I differs in magnitude from the voltage constant C_V ; the unit of the former is the ampere per millimeter (A/mm) or ampere per scale division (A/div), and the unit of the latter is the volt per millimeter (V/mm) or volt per division (V/div). A galvanometer used for testing of materials must have a current-to-response constant almost equal to 10^{-9} A/div. Knowing the constant C_I , we can find the current flowing through the galvanometer by the formula $I = C_I \alpha$, where α is the number of divisions by which the pointer has deflected in response to the current passing through the galvanometer. It should be kept in mind that the galvanometer constant marked on the instrument is given with an accuracy of $\pm 10\%$ which exceeds the limits of error allowable in testing of materials. This makes it necessary to determine the value of C_I just before testing.

There are three methods of current measurement with a galvanometer, known as the deflection method, comparison method, and the capacitor method.

Deflection method. The specimen of a material or component subject to testing is connected in the measuring circuit (Fig. 2.1) in series with a standard resistor R_0 (also

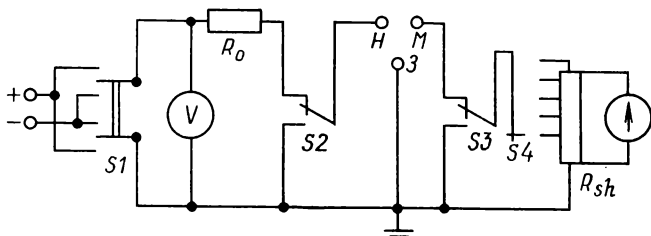


FIG. 2.1. Circuit diagram for measuring R_x by the direct deflection method and comparison method

called a resistance standard) calibrated to a precise resistance in the order of 1 M Ω . The galvanometer placed in the circuit is provided with a universal shunt R_{sh} to extend the current measurement range. The circuit is fed from a stabilized source of direct voltage. The source voltage can be adjusted from 0 to 5 000 V, control over the voltage being effected with a voltmeter V . The sign of voltage applied to the specimen can be changed with a reversing switch $S1$. Polarity reversal is necessary in testing of inhomogeneous materials. In this case the measurements are taken with the switch set in both positions; the arithmetic mean of the measurement results is then used in calculations. The leads running from the galvanometer to the measuring electrode M must be guarded with a shield, and the shield grounded. It is expedient to install all switches on polytetrafluoroethylene plates noted for high resistance and mount circuit components on a grounded metal sheet. According to safety rules, the circuit should be protected by a guard system which has auxiliary (guard) contacts to turn off the supply while replacing the specimen.

As noted above, a galvanometer is used to measure electric current in a circuit. Its sensitivity can be changed by varying the degree of shunting. Each step of shunting has

its shunt ratio n which is the ratio of the current through the galvanometer to the current in the circuit. This ratio is commonly set at 10^{-4} , 10^{-3} , 10^{-2} , 10^{-1} , and 1.

In order to measure a current, one should know the current constant C_I (or the scale factor).

This constant is found experimentally in the following manner. The terminals M and H for connecting respectively the measuring and the high-voltage electrode are shorted out, while the guard electrode is disconnected from the terminal \mathcal{J} . In these conditions, the current in the circuit is determined by the resistance R_0 of the accurately specified value. With the shunt switch $S4$ set in a position corresponding to the lowest current ($n = 10^{-4}$) and switches $S2$ and $S3$ in the upward positions, the supply is turned on to take readings α (in millimeters or scale divisions) on the galvanometer at a voltage U equal to 100 V. The galvanometer current constant C_I is computed by the formula

$$C_I = \frac{nU}{\alpha R_0}$$

The quantity C_I is generally determined at two values of voltage, and the sought-for value of C_I is found as the arithmetic mean of the calculated results.

To measure the resistance R_x of a specimen, the electrodes of the measuring cell are connected to the corresponding terminals H , M , and \mathcal{J} . The diagram of connections depends on the type of resistivity we have to determine, ρ_v or ρ_s . The switches $S2$ and $S3$ are thrown upwards. The switch $S4$ is first placed in a position corresponding to the lowest current ($n = 10^{-4}$). The source voltage is smoothly increased to reach the value specified in the standard on the material being tested. For solid and liquid dielectrics, this value is generally equal to 500 V, though other values are practicable too; for polymer films, the test voltage is kept under 10 V. Next the position of switch $S4$ is changed to set the galvanometer for a convenient indication. If the standard on a material under test does not prescribe the time of holding the specimen under the applied voltage before reading the galvanometer, then the readings α are taken 60 s after switching on the voltage supply. The fact is that the current flowing through a specimen drops with time to a certain steady value called the leakage current. So, to ensure the

reproducibility of test results, it has become an established rule to take readings some definite time after applying the voltage. The resistance R_x of a specimen is calculated by the formula

$$R_x = \frac{nU}{\alpha C_I}$$

On completing the measurements, the switch $S2$ should be thrown downwards to discharge the specimen.

To measure R_x to a specified accuracy, the error for the applied voltage and for the shunt resistance R_{sh} must be under 0.5%, and the error for the resistance R_0 below 1%.

Comparison method. This method is in essence a variety of the previous method, the difference being in the procedure of measurements and calculations. The circuit diagram and measuring instruments are the same as in the deflection method (Fig. 2.4). The principle of the method lies in the two-stage measurement of current in the circuit, first, with the specimen connected to the circuit, and, second, with the specimen shorted out, the voltage U being kept invariable. In the first measurement

$$I_1 = \frac{U}{R_0 + R_x}$$

In the second measurement

$$I_2 = U/R_0$$

Using the above expressions, we find the specimen resistance

$$R_x = (I_2/I_1 - 1) R_0 \quad (2.1)$$

Expressing I through the galvanometer reading α , shunt ratio n , and galvanometer constant C_I , we obtain

$$I = \alpha C_I / n \quad (2.2)$$

Substituting Eq. (2.2) into Eq. (2.1) gives

$$R_x = R_0 \left(\frac{\alpha_2 n_1}{\alpha_1 n_2} - 1 \right) \quad (2.3)$$

The standard resistance R_0 must be in the order of $10^7 \Omega$ and be kept practically constant with changes in ambient temperature. The resistance standards employed for the purpose must show a temperature coefficient under 10^{-4} K^{-1} .

Measurements are done in the following manner. Connecting a specimen to the circuit and placing the shunt switch $S4$ in the position at which $n = 10^{-4}$, while throwing the switches $S2$ and $S3$ upwards, we adjust the desired voltage from the voltmeter indication and determine the deflection α_1 of the galvanometer. If the deflection is insignif-

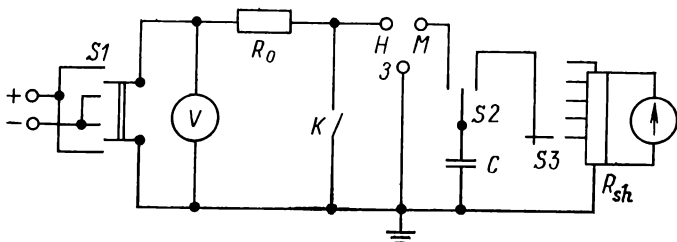


FIG 2.2. Circuit diagram for measuring R_x by the capacitor method

icant, we turn the switch for the next step of the shunt and take the measurement. The second measurement for determining α_2 , with the terminals H and M shorted out, is similar to the first measurement procedure. After completing the measurements, it is necessary to discharge the specimen by throwing the switch $S2$ downwards and bring the shunt switch to the initial position to set n at 10^{-4} . The resistance R_x is then found from formula (2.3).

As with the deflection method, the comparison method offers the possibility of measuring high resistances, of the order of $10^{13} \Omega$. The error of measurement with this method depends on the stability of supply voltage, error of the resistance R_0 and its temperature stability. Note that the galvanometer current constant does not enter into the calculation expressions. Using a stabilized voltage source and a resistance standard with R_0 accurate to within $\pm 2\%$, the comparison method can measure R_x to better than $\pm 5\%$.

Capacitor charge method. In this method, as with the above methods, the specimen resistance R_x is measured indirectly, in terms of the current I traversing the specimen. Here, the specimen is connected in series with a capacitor C (Fig. 2.2) that charges for a certain time with the current I .

If the capacitor charges via the specimen resistance R for time t from the source of voltage U , then the voltage across the capacitor and its charge are respectively equal to

$$u_c = U(1 - e^{-\frac{t}{RC}}), \quad Q = CU(1 - e^{-\frac{t}{RC}})$$

The expression $e^{-t/(RC)}$ can be expanded into a series

$$e^{-\frac{t}{RC}} = 1 - \frac{t}{RC} + \frac{t^2}{(RC)^2 \cdot 2!} - \dots$$

At $t \ll RC$, the expansion can be limited to the first two terms of the series. The charge is then given by

$$Q = CU \left[1 - \left(1 - \frac{t}{RC} \right) \right] = \frac{Ut}{R}$$

Knowing the capacitor charge determined with a ballistic (quantity) galvanometer, we can calculate the specimen resistance. The ballistic galvanometer differs from a conventional type in that its moving system has an intentionally increased moment of inertia in order to detect small quantities of electricity (the discharge current) moving during short periods of time. The basic characteristic of a ballistic galvanometer is its ballistic constant C_Q marked on the scale. The error for the ballistic constant, however, is too large, $\pm 10\%$. This makes it essential to estimate the value of this constant before taking the measurements, using for the purpose the circuit diagram shown in Fig. 2.2. First we make sure that the switch $S1$ is in the midposition (the voltage source is off), switch K in the on position, and switch $S2$ in the midposition. Next it is necessary to short out the terminals H and M , leaving the terminal 3 intact, turn on the switch $S1$ and thus connect the circuit to the voltage supply, place the switch $S2$ in the left position, and then set the switch K in the off position. In this case the capacitor charges through the resistance R_0 for a definite time t . As this time elapses, we put the switch $S2$ in the right position to enable the capacitor C to discharge into the galvanometer and note a maximum deflection α of the meter. The capacitor charge here is

$$Q = tUR_0$$

The galvanometer ballistic constant is then found from the formula

$$C_Q = \frac{tUn}{R_0\alpha}$$

The resistance R of a specimen is measured in the following manner. First, we connect the measuring cell to terminals H , M , and β , place the switch $S2$ in the left position and switch K in the off position to allow the capacitor C to charge as a rule for 5 min. Next we set the switch $S2$ in the right position to cause the capacitor to discharge into the galvanometer noting the first largest deflection α of the meter. In this case the shunt switch $S\beta$ must be placed in the position corresponding to $n = 10^{-4}$. If the instrument shows an insufficient deflection, the measurements should be repeated at a larger value of n . The resistance R_x of the specimen is computed by the formula

$$R_x = \frac{tUn}{\alpha C_Q}$$

After completing the test, the switch K is put in the on position to discharge the specimen, and the switch $S\beta$ is placed in the position corresponding to $n = 10^{-4}$.

The error of measurement with this method largely depends on leakage currents through the capacitor and through the switches, electrode system, and other elements of the measuring set. Besides, it should be remembered that the resistance of a specimen depends on the applied voltage and time of its action, which vary in the course of measurements. That is why this method causes a larger measurement error than the deflection method.

The use of galvanometers for measuring resistances R_x is limited by the lowest value of current they are still able to detect; this value is equal to 10^{-10} A for the best moving-coil galvanometers. The resistance measurement range of instruments responsive to this value of current at 1000 V comes to $10^{13} \Omega$. Tests on many electrical insulating materials which have higher resistances call for more sensitive instruments.

2.3. Measurements with Electrostatic Electrometers

Electrostatic electrometers are high-sensitive high-input resistance devices which rely on an electrostatic measuring system. By design, these are divided into quadrant, string (filament), and torsion electrometers.

In a quadrant electrometer (Fig. 2.3), the moving system consists of an electrode 1 from thin metal foil suspended on a quartz string 2. The moving electrode is made fast to a mirror 3 and placed inside stationary electrodes 4 (quadrants of the vertical metal cylinder). The figure shows the diagram of connection of electrodes that offers the highest sensitivity. The axis of rotation of the moving electrode must coincide with the axis of symmetry of the quadrants. A voltage U_x impressed across the terminals causes elec-

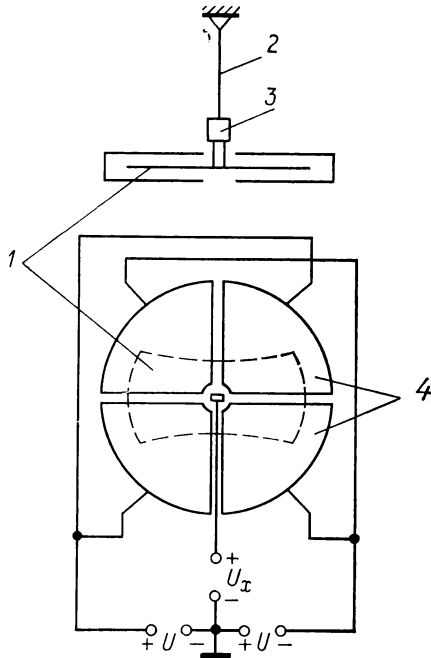


FIG. 2.3. Schematic of quadrant electrometer

trostatic forces to appear between the moving and fixed electrodes. These forces displace the suspended electrode and twist the suspension fiber. With the suspended electrode set up in a new position, the torque produced by the electrostatic forces will be equal to the counter (restoring) torque that tends to untwist the fiber. The theory that relates to the instrument in question shows that the angle of rotation, α , of the moving system is proportional to the voltage being

measured:

$$\alpha = \frac{2}{W} \frac{\partial C}{\partial \alpha} U U_x$$

where W is the counter torque that results from twisting of the fiber; C is the capacitance between the moving electrode and the two opposite quadrants electrically connected with each other; and U represents auxiliary voltage.

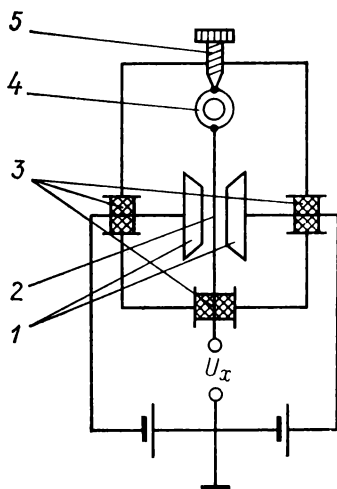


FIG. 2.4. Simplified arrangement and connection diagram of a string electrometer

For measuring the angle of turn, α , the moving system uses a narrow light beam reflected from the mirror.

The voltage constant of the device, with a millimeter scale 1 m distant from the mirror, ranges up to 10^{-3} V/mm. The insulation resistance of the moving system is not less than 10^{17} Ω . The input capacitance C_{in} of the electrometer is equal to about 20 pF.

A string electrometer (Fig. 2.4) consists of two narrow fixed electrodes 1 in the form of plates and a movable string electrode 2, which is a platinum fiber 1 to 5 μm thick and 50 to 100 mm long, stretched midway between the two con-

ducting plates. The lower end of the string is attached to an amber insulator 3, and the upper end to a quartz ring 4 and, via the latter, to a micrometer screw 5 intended for a fine adjustment of string tension. The gap between the plates, also fastened to amber insulators, can be varied. On applying, say, a positive potential to the string, the negative plate will begin to attract the string and the positive repulse it. This will cause the string to bend until the string's elastic forces counterbalance the electrostatic forces. The displacement of the string in its midportion can be observed under a microscope provided with an eyepiece scale.

The electrometer constant C_U depends on string tensioning and the spacing between the electrodes: the higher the tension and the larger the interelectrode gap, the greater the constant. Its value can range up to 10^{-2} V/mm. Since the constant C_U depends on the string tension and interelectrode distance, it is necessary to calibrate an electrometer before taking measurements. The Soviet-made type ЭС-2 electrometer has a constant C_U of 3×10^{-3} to 4×10^{-3} V/div, input capacitance of 5 pF, and auxiliary battery voltage of 75 to 80 V.

String electrometers are less sensitive than quadrant counterparts, but show a better reproducibility of test data, lower input capacitance, and shorter damping time. Torsion electrometers combine the features of string and quadrant electrometers. The type ЦТ-1М torsion electrometer has a constant C_U equal to 2×10^{-2} V/div and input capacitance to 2.5 pF.

It is clear from the above that electrometers measure voltages. An electrometer can measure currents only if its circuit incorporates precision resistor of high resistance R_0 . In this case, the electrometer indicates the voltage drop across the standard resistance R_0 as the current being measured, I , passes through it.

The resistance R_x of a test specimen can be measured by the method of direct deflection or by the compensation method.

Deflection method. This method uses a conventional three-electrode system (see Fig. 1.1), but here a high-resistance standard R_0 connected in parallel with an electrometer (Fig. 2.5a) replaces a shunt with a galvanometer. Since the resistance standard R_0 is connected in series with the specimen resistance R_x , the voltage U_{el} measured by the electrometer is

$$U_{el} = IR_0 = \frac{U}{R_0 + R_x} R_0$$

where U is the voltage applied to the measuring circuit; and I is the current in the circuit. Hence

$$R_x = (U/U_{el} - 1) R_0$$

If the applied voltage U considerably exceeds the voltage U_{el} on the electrometer, that is, $U \gg U_{el}$, then

$$R_x = \frac{U}{U_{el}} R_0$$

It is seen from the above formula that the measurement error for R_x depends on that for U and R_0 .

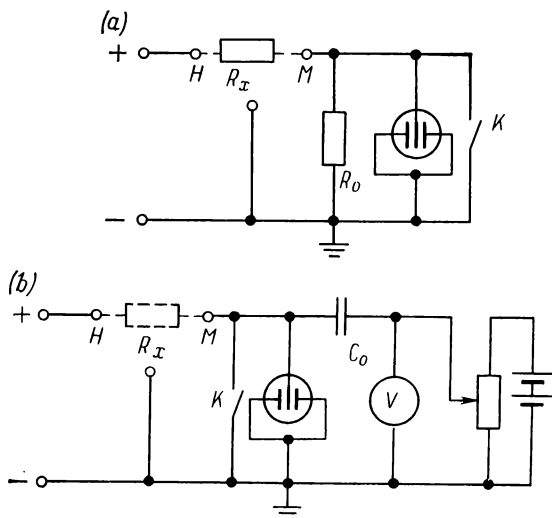


FIG. 2.5. Circuit diagrams for measuring R_x with an electrostatic electrometer

(a) by deflection method; (b) by compensation method

The limiting percent error of resistance measurement with an electrometer

$$\delta R_x = \delta U + \delta R_0 + \delta U_{el}$$

If the limiting measurement error for voltage U is within $\pm 0.5\%$, for resistance R_0 within $\pm 2\%$, and the permissible error limits for an electrometer are $\pm 1\%$, then the limiting percent error

$$\delta R_x = 0.5 + 2 + 1 = 3.5\%$$

The volume and surface resistivities of a material are calculated with common formulas. High-resistance measu-

rements require the use of standard resistors with R_0 up to $10^{12} \Omega$. Composite resistors of this resistance range are now available to the measuring technique. If the electrometer constant is $C_{el} = 10^{-2}$ V/mm, test voltage $U = 1000$ V, and $R_0 = 10^{12} \Omega$, then we can find the upper limit of resistance R_x the electrometer is still able to measure:

$$R_x = \frac{1000}{10^{-2}} 10^{12} = 10^{17} \Omega$$

It should be noted, however, that the electrometer capacitance C_{el} charges through the specimen resistance R_x . The transient process of deflection of the moving system practically takes rather long time, 3 to 5 times the circuit time constant τ . The process of measurement thus turns out to be fairly long, which is a severe drawback of this method.

Compensation method. As in the above method, this method uses a common three-electrode system and also a capacitor of capacitance C_0 , a voltage compensating circuit, and an electrometer (Fig. 2.5b). The capacitor first charges for some time t from the circuit supply source through the specimen resistance R_x . The voltage U_C across the capacitor is balanced out by an auxiliary voltage U_p derived from a potentiometer and measured with a voltmeter. The electrometer serves in this case as a null-indicator that does not use electric current; if the deflection of the electrometer is zero, then

$$U_C = U_p$$

Neglecting the leakage current through the capacitor and electrometer, the capacitor charge in a time t will reach

$$q_t = \frac{U}{R_x} t$$

On the other hand, this charge is proportional to the capacitor voltage U_C :

$$q_t = C_0 U_C = C_0 U_p$$

Equating the right-hand terms of the two equations gives

$$R_x = \frac{tU}{U_p C_0}$$

where U is the circuit supply voltage, and U_p is the compensating voltage indicated by the voltmeter.

From the above equation it follows that the capacitance C_0 , time t , and voltages U and U_p should be measured to the highest possible accuracy. Besides, the insulation resistance of the capacitor and electrometer must be rather high. If the test voltage is $U = 1000$ V, $t = 300$ s, $U_p = 0.1$ V and $C_0 = 30$ pF, then

$$R_x = \frac{10^3 \times 3 \times 10^2}{10^{-1} \times 30 \times 10^{-12}} = 10^{17} \Omega$$

The compensation method ensures a higher sensitivity than the deflection method, but calls for elimination of even small leakages in the circuit. In any metering circuit that incorporates an electrometer, high-voltage elements should be thoroughly shielded; this is particularly the case for the leads that convey voltage to the electrometer's moving system. A resistance measuring set should be well grounded. Amber or polytetrafluoroethylene insulators offer a high insulation level.

2.4. Electrometric Amplifiers

A voltage drop across any resistance can be measured with a vacuum tube voltmeter—a device consisting of a pointer indicator (a moving-coil voltmeter, for example) and an electronic amplifier. Where it is necessary to measure the voltage drop across a high resistance, as is the case in testing of insulating materials, the input resistance of the amplifier must be sufficiently high. The amplifiers which have a high input resistance ($10^8 \Omega$ and above) are called electrometric, or charge, amplifiers. As compared with electrostatic electrometers, voltmeters with electrometric amplifiers show a lower input capacitance and shorter damping time, though they are more complex in design.

Vacuum tube amplifiers. These amplifiers use both special electron tubes and some conventional types adapted to operate in electrometric conditions. An electrometer tube has four electrodes: an anode (metallic plate), cathode, control grid, and a cathode grid. The last electrode, also called a space-charge grid, is disposed between the control grid and cathode. Under the effect of the positively applied potential, the cathode grid produces an accelerating field, whereby

the tube can operate at low plate voltages. The insulation resistance of the control grid is as high as 10^{14} to $10^{15} \Omega$ owing to the arrangement of the control grid lead in the upper portion of the envelope and the use of special holders to fasten the grid inside the tube. Because of the high resistance and other features of the control grid, the intrinsic current on the grid is extremely small, less than 10^{-14} A.

This current mainly consists of three components. The first is due to transfer of a number of electrons from the cathode to the grid during operation of the tube. A negative bias applied to the grid helps minimize this component. The second component arises from the ionization of gas residues in the tube or disintegration of the cathode, and the third is due to the emission of electrons from the grid itself. To decrease the second component, the grid inside the tube is fastened on special glass holders which prevent conducting particles from impinging on its surface. Thermionic emission is decreased by lowering the temperature inside the tube, that is, the temperature of the cathode, using for the purpose special materials. An electrometer tube bulb is enclosed in a shell to exclude access for light, thereby making it impossible for external sources to produce a photoelectric effect.

To reduce ionization of the residual air, the plate voltage is kept low, down to 20 V. At such a voltage and with a negative bias on the control grid, the grid current becomes very small.

In order to produce a sufficiently high plate current with a negative bias and low plate voltage, an additional grid is placed between the grid and cathode, and a positive potential of about +3 V is applied to this grid, the negative potential of about -3 V being maintained on the control grid. Under these conditions, the transconductance S of Soviet-made electrometer tetrodes of the types ЭМ-5 and ЭМ-6 reaches 50 mA/V and the grid current is equal to 1×10^{-14} A.

Electrometer pentodes offer a higher transconductance, but have a larger grid current. The type ЭМ-8 pentode, for example, has a transconductance of 800 μ A/V at a nominal plate voltage of 15 V, but its grid current is rather high 1×10^{-10} A.

The principle that underlies the measurement of weak

currents with a vacuum-tube electrometer comes to the following. The current I_x passing through a specimen resistance R_x causes a voltage drop ΔU across a standard resistance R^* ($R^* \ll R_x$):

$$\Delta U = IR^*$$

The resistance R^* is placed between the control grid and cathode. The voltage ΔU is applied to the control grid,

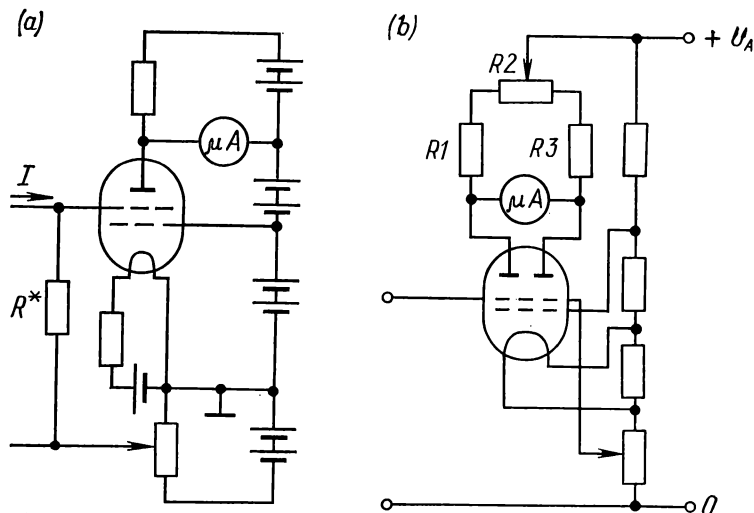


FIG. 2.6. Circuit diagrams of vacuum tube electrometers

amplified, and indicated by a pointer meter (Fig. 2.6a). A variation in the plate current on the linear portion of the vacuum tube characteristic

$$\Delta I_p = S \Delta U = IR^*S$$

Hence, the current gain factor

$$\mu_i = \frac{\Delta I_p}{I} = SR^*$$

For example, at $R^* = 10^{11} \Omega$, $S = 25 \mu A/V$, the current gain $\mu_i = 10^{11} \times 25 \times 10^{-6} = 2.5 \times 10^6$.

It can easily be shown that even one electrometer tube is enough to measure high resistance, exceeding $10^{15} \Omega$. Indeed, if we place a microammeter with a scale factor of C into a plate circuit, then the current being measured

$$I = \frac{\Delta I_p}{SR^*} \geq \frac{C}{SR^*} = \frac{C}{\mu_i}$$

The effective range of resistance measurement

$$R_x = \frac{U}{I} \leq \frac{\mu_i U}{C}$$

At $C = 1.0 \mu A$, $U = 500 \text{ V}$, $\mu_i = 2.5 \times 10^6$, we get

$$R_x \leq \frac{500 \times 2.5 \times 10^6}{10^{-6}} = 1.25 \times 10^{15} \Omega$$

It is seen that even the simplest circuit with an electrometer tube shows a high sensitivity.

But the use of an electrometer tube involves difficulties largely associated with continuous and fast oscillations of the microammeter pointer about the midposition (zero point) and gradual deviation of the zero reading from the calibrated point (the effect is known as zero drift). The shift of zero results from changes in tube characteristics (changes in emission) and variations in the voltage of a supply source. The battery voltage varies as the battery discharges. The use of a battery preliminarily discharged to one-fourth of its capacity or a well stabilized rectifier permits decreasing the effect of voltage variations. Zero shift can be effectively diminished using a double-balanced electrometric amplifier based on the ЭМ-6 type double tetrode (Fig. 2.6b). Here the end instrument, μA , is placed across a pair of opposite junctions of a bridge in which resistors $R1$ and $R3$ form one pair of arms and the tube's internal resistances the other pair. With the bridge circuit being balanced, changes in the supply voltage, cathode emission or temperature will not disturb the balanced state since all these factors will have an equal effect on the two (conjugate) branches of the bridge. Resistor $R2$ serves for the initial zero adjustment of the instrument.

One-stage amplifier circuits of electrometers have at present given way to multistage amplifier circuits of high

amplification and with a large amount of feedback. In these circuits, it is possible to hold the input capacitance C_{in} down to 1 pF and thus ensure a rather small time constant at $R^* = 10^{12} \Omega$:

$$\tau = R^* C_{in} = 10^{12} \Omega \times 1 \times 10^{-12} F = 1 \text{ s}$$

Vacuum tube electrometers are able to measure the resistance R_x of specimens up to $10^{17} \Omega$ at a test voltage of 1 000 V.

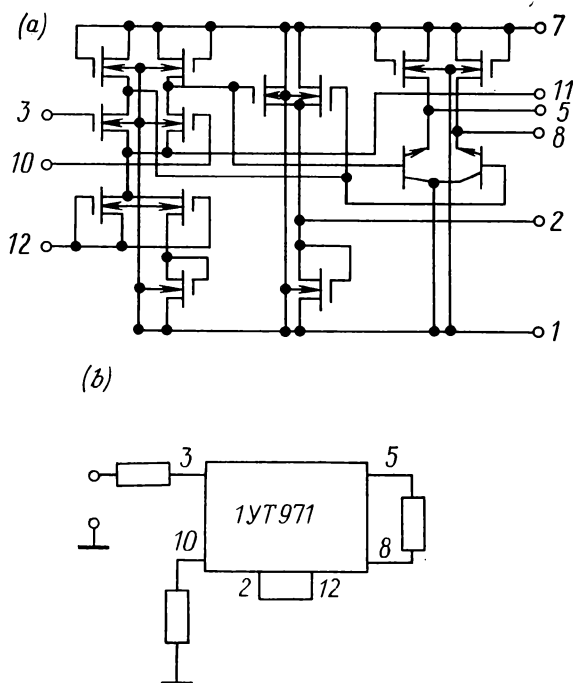


FIG. 2.7. Electrometric transistor amplifier
(a) circuit diagram of an integrator; (b) connection diagram

Until very recently, transistor amplifiers did not find use at all for electrometric purposes, or, where they did, it was necessary that the amplifiers incorporate vacuum tube input stages. That was because at the time transistor devices had low input resistance. With the advent of MOS-

FETs (field-effect transistors with a metal-oxide-semiconductor structure), the situation changed drastically. These transistors represent a voltage controlled device with a high input resistance (10^{12} to $10^{14} \Omega$) which remains stable irrespective of the value and polarity of the input voltage. The input current in these transistors is negligible even at increased temperatures. These features of MOS transistors are put to use in electrometer amplifiers. Fig. 2.7*a* illustrates the circuit diagram of a 1YT 971 type integrator. This amplifier has two double-balanced stages. The first stage is built on MOS transistors, and the second on n - p - n triodes. The input current of such an amplifier does not exceed 50 pA, the input resistance is a function of the substrate insulation resistance, and the voltage amplification factor is not below 10. The connection diagram of the amplifier is given in Fig. 2.7*b*.

2.5. Electronic Megohmmeters and Teraohmmeters

Electronic devices find expanding applications in measuring high resistances, up to $10^{17} \Omega$. The measurement error varies from 1.5 to 2.5% for the resistance measuring range of up to a thousand megohms and reaches 10 to 20% as the measuring range extends. The simplest megohmmeter or teraohmmeter operates on the principle of measuring the voltage taken from a divider that consists of a resistance R_x and standard resistance R_0 (Fig. 2.8*a*). The basic components of the measuring instrument are thus an input voltage divider, vacuum tube voltmeter, and supply source. At a supply voltage U_0 , the voltage measured by the voltmeter will be equal to

$$U_x = U_0 \frac{R_0}{R_0 + R_x}$$

The voltmeter scale is calibrated to read resistance R_x directly in the direction from right to left (the extreme right mark corresponds to $R_x = 0$, and the extreme left mark to a maximum value of R_x). It is easy to see that the measurement error here depends on the error of resistance R_0 , test voltage U_0 , and voltmeter error, so that the total error is generally rather high.

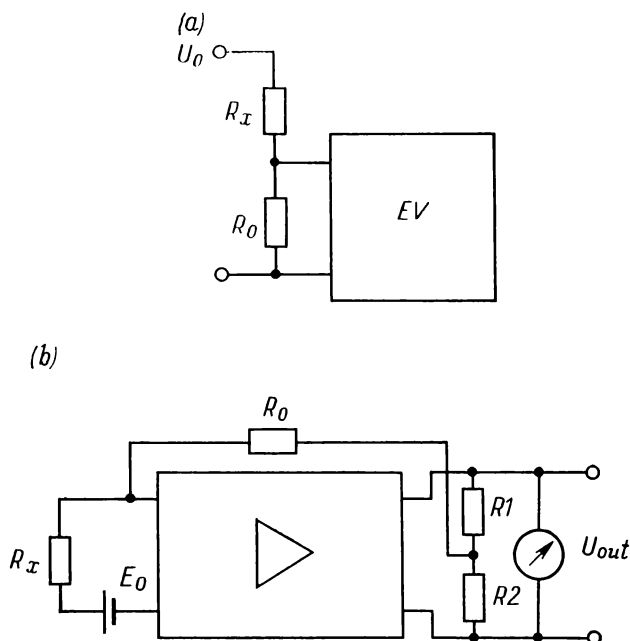


FIG. 2.8. Electronic megohmmeters

In Fig. 2.8*b* is illustrated the diagram of a megohmmeter which is an amplifier with R_x connected across its input terminals. If the gain of the amplifier is sufficiently high, then

$$U_{out} = \frac{R_0 (R_1 + R_2) E_0}{R_2 R_x}$$

As seen from the expression, the output voltage U_{out} is inversely proportional to R_x . It is also apparent from this same expression that the output voltage is independent of the amplification factor, so that the measurement error will result only from the error for resistors and the error for E_0 . This device can measure resistances which are a few orders of magnitude higher than the resistance R_0 . For example, the range of measurement of R_x for a EKG-7 teraohmmeter at $R_0 = 10^{12} \Omega$ comes to $10^{17} \Omega$. It is com-

mon to insert in the measuring circuit a few resistors of R_0 to enable changing over from one range of measurement to another. Since standards specify various test voltages for materials, the designs of measuring devices allow for a stepwise change of E_0 from 1 to 1000 V, the end instrument scales being graduated in units of resistance.

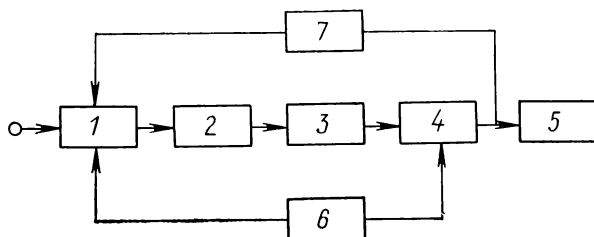


FIG. 2.9. Block diagram of a set for measuring high resistances and small currents

The Soviet industry puts out multimeters designed to measure high resistances, small direct currents and direct voltages. These devices satisfy all the above-mentioned requirements. A typical block diagram of one such device appears in Fig. 2.9. The basic component of the device is an amplifier 3 with a high gain (5 000 and over). An electrometer preamplifier 2 connected to the input circuit serves to increase the input resistance. This preamplifier uses special vacuum tubes or field-effect transistors and has an input resistance of 10^{12} to $10^{15} \Omega$ at a small gain (near 10). Since direct current (voltage) amplification involves difficulties due to the time and thermal drift of vacuum-tube and transistor characteristics, the amplifier operates on the so-called modulation-demodulation basis (modern principle): a modulator 1 transforms the input voltage into alternating voltage which is amplified by an a.c. amplifier and then rectified by a phase-sensitive rectifier 4 (demodulator). The thermal drift in modern amplifiers is one-tenth to one-hundredth that for double-balanced d.c. amplifiers. A generator 6 serves for synchronous switching of the modulator and demodulator. The modulation frequency does not generally exceed 1 000 Hz. A negative feedback loop 7 placed around the entire amplifier provides for more stable amplifier

gain. The end instrument 5 here is commonly a moving-coil microammeter with a few scales graduated respectively in terms of current, voltage, and resistance.

Naturally, one concrete device or another may not contain some of the above components. Thus, instead of an MDM amplifier it is possible to employ some other amplifier in which a modulator and demodulator will be absent. Measuring devices can be of the vacuum-tube or transistor type, or, sometimes, can incorporate both vacuum tubes and transistors. Consider some types of teraohmmeters.

The type EK6-11 vacuum-tube teraohmmeter is designed to measure R_x at test voltage of 2.5, 5, 7.5, 10, 25, 50, 75, 100, 250, 500 V. Given a special supply source, the set can measure at a test voltage of 1 000 V, which is an advantage of the device. The resistance measuring range is 3×10^7 to $10^{15} \Omega$. The indicating instrument has a scale graduated in gigaohms: 1, 3, 10, 30, 100, 300 G Ω and a scale laid out in teraohms: 1, 3, 10, 30, 100, 300, 1 000 T Ω . The device is accurate to within $\pm 6\%$ at R_x of less than $10^9 \Omega$ and to $\pm 10\%$ if R_x is less than or equal to $10^{15} \Omega$. The set has an interlock-protected chamber for test specimens. The time of measurement does not exceed 1 min even if R_x approaches $10^{15} \Omega$, which is a point in the favor of the device.

The type EK6-7 vacuum-tube teraohmmeter, now in commercial production, is more equal to the job than other types of electrometer. The test voltages applied to a specimen can be of the following values: 1, 10, 100 to 1 000 V. The resistance measuring range of the device extends from 10^7 to $10^{17} \Omega$. The readings of the measured resistance can be taken on a scale graduated in gigaohms from 10 to 100 G Ω or on a scale graduated in teraohms: 1, 10, 100, 10^3 , 10^4 , 10^5 T Ω . The measurement error (for the upper limit of the corresponding scale) is within $\pm 4\%$ at $R_x \leq 10^{12} \Omega$, $\pm 6\%$ for $R_x \leq 10^{15} \Omega$, and $\pm 10\%$ for $R_x \leq 10^{17} \Omega$. The error of measurement depends on the test voltage. The set is complete with a shielded chamber for test specimens, which helps eliminate the effect of strays in measuring the specimen resistance. This chamber serves at the same time as a case for the set itself. The device circuit can provide for additional shield (guard) voltage obtained from the amplifier output; the guard circuit decreases the effect of stray currents on

the result of measurement of high resistances. The presence of shield voltage permits the voltage drop across the resistance R_0 at a certain test voltage to be disregarded when measuring extremely small currents. The set contains a box of precision resistance R_0 (10^8 , 10^9 , 10^{10} , 10^{11} and 10^{12} Ω), electrometric d.c. amplifier, direct voltage source for obtaining accurate values of test voltages (1, 10, 100 and 1 000 V), and a stabilized power unit.

The standard resistance box effectively eliminates the influence of stray leakage currents by virtue of insulating plates and high-quality insulators. The set uses a balanced circuit to amplify the direct current being measured. The first stage uses an 9M-6 vacuum tube.

A universal E6-14 teraohmmeter comes in a fully transistorized design, which can measure resistances from 10^7 to 10^{17} Ω , direct currents from 10^{-7} down to 10^{-15} A, and d.c. voltages from 1 mV to 10 V. The input resistance of the device in measuring d.c. voltages is no less than 10^{15} Ω .

PERMITTIVITY AND LOSS ANGLE AT LOW FREQUENCIES

3.1. General

Electrical insulating materials exposed to an electric field display the ability to store electric energy. The energy w' stored up in a unit volume is proportional to the square of field strength E and to the absolute dielectric constant $\epsilon\epsilon_0$ which is the product of the relative dielectric constant ϵ (relative electric permittivity, or permittivity for short, of a material) and the electric constant ϵ_0 (permittivity, or capacitivity, of free space):

$$w' = \frac{1}{2} \epsilon\epsilon_0 E^2$$

The energy w' rises with field strength E , and vice versa. This process most often entails irreversible processes of energy dissipation in an insulating material in the form of heat. Note that the dissipation of electric energy takes place not only when a material is placed in an a.c. field but also in a d.c. field. However, the processes occurring in a material subjected to alternating voltage play a more important part. The electric energy expended by an electric field in a material is known as dielectric loss (power loss).

Consider an insulation specimen fitted out with electrodes to which an a.c. voltage is applied.

A lossy specimen may be represented by a series or parallel equivalent circuit (Fig. 3.1). It is obvious that regardless of the choice of the equivalent circuit, a number of the parameters which describe the chosen circuit must remain invariable. To these belong the phase shift φ which is an angular difference in phase between the current I in a series portion of the circuit and the voltage drop U in the entire circuit, the values of current I , and the dielectric loss P . Using these parameters, we can derive the relation

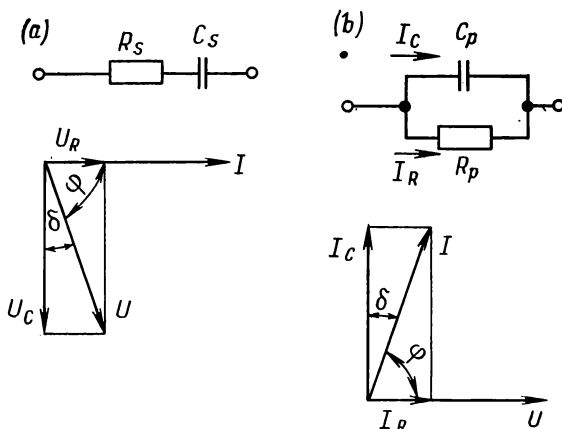


FIG. 3.1. Equivalent circuits and phasor diagram for an insulation specimen

(a) series circuit; (b) parallel circuit

between the equivalent values of capacitance and of resistance for both circuits.

For the series equivalent circuit (Fig. 3.1a), the following relations hold true:

$$\tan \delta = \omega C_s R_s \quad (3.1)$$

$$I = U \omega C_s \cos \delta$$

$$P = I^2 R_s = U^2 \omega C_s \frac{\tan \delta}{1 + \tan^2 \delta} \quad (3.2)$$

For the parallel circuit (Fig. 3.1b)

$$\tan \delta = \frac{1}{R_p \omega C_p} \quad (3.3)$$

$$P = U^2 \omega C_p \tan \delta \quad (3.4)$$

Equating pairwise the right-hand sides of equations (3.1) and (3.3) and also (3.2) and (3.4), we obtain the set of two equations whose solution gives the relations

$$C_s = C_p (1 + \tan^2 \delta) \quad (3.5)$$

$$R_s = R_p \frac{\tan^2 \delta}{1 + \tan^2 \delta} \quad (3.6)$$

Relations (3.5) and (3.6) between the parameters of equivalent circuits become yet simpler if $\tan \delta \ll 0.1$. Since in this case $\tan^2 \delta \ll 0.01$, then, if the error does not exceed $\pm 1\%$, it is safe to assume that

$$C_s = C_p \quad (3.7)$$

$$R_s = R_p \tan^2 \delta \quad (3.8)$$

The capacitance C_p in the parallel equivalent circuit is in the main taken as the sought-for capacitance C_x of the specimen or product.

The dielectric permittivity of a material under test is calculated by preliminarily measuring the specimen capacitance C_p in the parallel equivalent circuit or the capacitance C_s in the series circuit. It is common to find a relative permittivity ϵ (relative to $\epsilon_0 \approx 8.854 \times 10^{-12}$ F/m). Elsewhere in this book we shall call ϵ just permittivity for brevity.

To calculate the permittivity ϵ of a material, we can rely on the fact that the capacitance of a capacitor is a function of the capacitor's geometric dimensions and the permittivity of its dielectric. For a flat specimen (see Fig. 1.1), the capacitance C_x is expressed in the form

$$C_x = \epsilon \epsilon_0 \frac{F}{t} \quad (3.9)$$

where F is the effective area of electrodes; t is the specimen thickness; and ϵ is the permittivity of the material under test. It is obvious that a capacitor of the same electrode dimensions but with a vacuum for its dielectric will have the capacitance

$$C_0 = \epsilon_0 \frac{F}{t} \quad (3.10)$$

Dividing Eq. (3.9) by Eq. (3.10) gives

$$\epsilon = C_x / C_0 \quad (3.11)$$

Thus the permittivity ϵ of a specimen can be calculated from the results of measurement of C_x and C_0 . The value of C_0 is more often determined from the calculation. The loss tangent $\tan \delta$ (dissipation factor) may be found by direct measurements or from the results of indirect measurements with formulas (3.1) and (3.3).

3.2. Specimens and Electrodes

The permittivity ϵ and $\tan \delta$ of solid electrical insulating materials exposed to a 50-Hz field are determined on flat (round or square) specimens and on tubular or shaped specimens. Flat and tubular specimens have the same dimensions as those used for measuring ρ_v and ρ_s (see Sec. 1.2).

If a material has a large thickness which does not permit determining ϵ and $\tan \delta$ in the direction perpendicular to its surface or layers, one resorts to shaped specimens. A groove cut in a specimen should have such a depth that the insulation thickness between the electrodes can be equal to 3 mm (see Fig. 5.2*b, d*). The requirements the specimens must meet are the same as those imposed on specimens used for estimating conductance. Electrodes can be made from the same materials, graphite being excepted. Measurements are performed by using a three-electrode system that consists of a high-voltage, guarded, and a guard electrode.

For insulating liquids, ϵ and $\tan \delta$ are determined with the aid of the system of flat or cylindrical electrodes described above (see Fig. 1.10). The measurements are done on a minimum of two samples, each not less than 50 cm³ in volume. The requirements on the electrodes and their design and also the procedures of preparing the measuring cell remain similar to those considered in Sec. 1.3.

The type of measuring cell (flat or cylindrical, two-terminal or three-terminal) is given in the standard or specifications on a concrete kind of insulating liquid. Two-terminal cells are allowable for use in making approval tests or incoming and periodic checks if, of course, the standard on a particular liquid does not prohibit employing these cells. In all other cases three-terminal cells must be used.

Before taking measurement, the cell is cleansed with a test liquid. This done, the test sample is poured into the cell, ensuring that the level of the liquid is 3 to 5 mm above the lower edge of the guard electrode. If the viscosity of test liquids at 20°C exceeds 50×10^{-6} m²/s (50 cSt), these must be preheated to 40-60°C. The temperature at which a liquid must be tested for ϵ and $\tan \delta$ is specified in the pertinent standard. If this temperature differs from the room temperature, the cell is placed in a thermostatic oven,

heated to the desired temperature, and left to stay in the oven for no less than 20 min.

The standards impose additional requirements on some materials and components. Thus, ϵ and $\tan \delta$ of capacitor and transformer oils at a frequency of 50 Hz must be determined at a field strength of 1 MV/m; ϵ and $\tan \delta$ of pertinax (the frequency being the same) must be determined on flat and round specimens not over 2 mm thick at a test voltage of 1 000 V.

When making a choice of specimen dimensions, it should be borne in mind that the capacitance of a capacitor formed by the specimen and electrodes must be sufficient to keep the capacitance measurement error within 1%. The lead for the guarded electrode and the connections to the indicating instrument must be shielded, with the shield grounded.

3.3. Measurements of C and $\tan \delta$ at 50 Hz

From the above it follows that for determining ϵ and $\tan \delta$ of a material we should measure C_x and $\tan \delta$ of the test specimen. The measuring circuits used for determining these characteristics at a frequency of 50 Hz are as a rule bridge circuits. The capacitance measuring range of the a.c. bridge employed shall be enough to cover the capacitance C_x of a test specimen. Also, the loss tangent measuring range of the bridge shall be approximately twice as large as the measured values of $\tan \delta$. The voltage and time of holding the specimen under test conditions are generally given in the standard or specifications on the material. If the standard does not stipulate these conditions, the test voltage shall be equal to 1 000 V. The measurement error shall be below $\pm(0.05 \tan \delta + 2 \times 10^{-4})$. A bridge whose circuit diagram is shown in Fig. 3.2 can measure C_x and $\tan \delta$ to such degree of accuracy.

The bridge is energized through a step-up transformer whose primary voltage can be adjusted to raise the voltage on the H. V. side to 10 kV. This voltage is applied across the grounded junction of resistance arms and the opposite "high-voltage" junction. The two adjacent arms connected at the high-voltage junction are capacitance arms; the test

specimen of capacitance C_x is placed in one of the two arms and the high-voltage standard capacitor of capacitance C_0 (equal to 100 pF) in the other arm. The guard electrode of the specimen is connected to a grounded

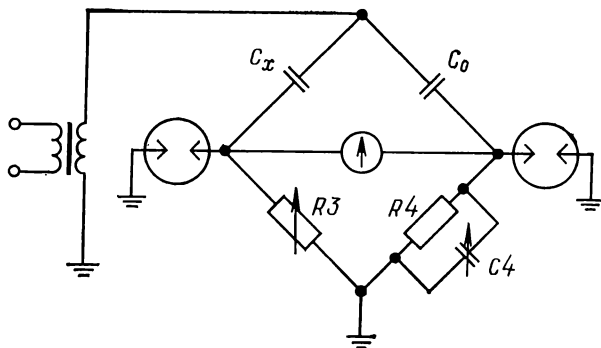


FIG. 3.2. Circuit diagram of a high-voltage bridge for measuring C_x and $\tan \delta$

shield and the high electrode to the high-voltage junction. The other pair of arms has a variable resistor R_3 and a fixed resistor R_4 shunted by a variable capacitor C_4 . In such a circuit all the voltage is practically impressed on the capacitance arms because the impedance (capacitive reactance equal to $1/\omega C$) the two capacitors offer to a.c. is much larger than the resistance of the resistors inserted in the other arms. So, despite the high voltage, it is quite safe to balance the bridge by varying R_3 and C_4 . The bridge network has dischargers to guard the circuit against high breakdown voltages (in case of the specimen rupture). The null indicator used in the bridge is commonly a vibration galvanometer (see below) often connected to the network through an amplifier.

The bridge is at balance if the products of impedances of the opposite arms are equal. In complex form, the equation may be written as

$$Z_x Z_4 = Z_0 Z_3 \quad (3.12)$$

Presenting each complex impedance in exponential form, we obtain

$$z_x z_4 e^{j(\varphi_x + \varphi_4)} = z_0 z_3 e^{j(\varphi_0 + \varphi_3)} \quad (3.13)$$

Here z_x , z_4 , z_0 , and z_3 are moduli of the complex impedances; and φ_x , φ_4 , φ_0 and φ_3 are arguments of the moduli, or phases. Thus, to balance the bridge, two conditions should be met:

$$z_x z_4 = z_0 z_3, \quad \varphi_x + \varphi_4 = \varphi_0 + \varphi_3 \quad (3.14)$$

The two equalities taken as balance conditions imply that it is necessary to vary two parameters (for example, R_3 and C_4) to balance the bridge. By adjusting the parameters in steps, we can obtain a condition at which the active and reactive components of voltage approach zero. Let us represent the test specimen by a series equivalent circuit (see Fig. 3.1a). Then

$$Z_x = R_s - j \frac{1}{\omega C_s}, \quad Z_0 = -j \frac{1}{\omega C_0}, \quad Z_3 = R_3$$

$$Z_4 = \frac{1}{1/R_4 + j\omega C_4} = \frac{R_4(1 - j\omega C_4 R_4)}{1 + (\omega C_4 R_4)^2}$$

Substituting the expressions of complex impedances into Eq. (3.12) gives

$$\left(R_s - j \frac{1}{\omega C_s} \right) \frac{R_4(1 - j\omega C_4 R_4)}{1 + (\omega C_4 R_4)^2} = -j \frac{R_3}{\omega C_0} \quad (3.15)$$

Dividing the real and the imaginary terms of Eq. (3.15) and performing algebraic transformations, we get

$$\tan \delta = \omega C_s R_s = \omega C_4 R_4 \quad (3.16)$$

$$C_s = C_0 \frac{R_4}{R_3} \quad (3.17)$$

It is evident from Eqs. (3.16) and (3.17) that the capacitance C_s can be balanced by adjusting R_3 ; in this case balance equation (3.16) does not change in form. On the other hand, $\tan \delta$ can be balanced by adjusting C_4 without disturbing balance condition (3.17). This suggests that the scale of R_3 may be laid out in units of capacitance and the scale of C_4 in units of $\tan \delta$.

The test specimen represented by parallel equivalent circuit (see Fig. 3.1*b*) will have an impedance equal to

$$Z_x = \frac{1}{1/R_p + j\omega C_p} \quad (3.18)$$

After making transformation similar to those mentioned above, in this case, too, we obtain

$$\tan \delta = \omega R_4 C_4 \quad (3.19)$$

$$C_x = C_0 \frac{R_4}{R_3} \frac{1}{1 + \tan^2 \delta} \quad (3.20)$$

The bridge arrangement considered here permits taking measurements at high voltages since the adjustable elements

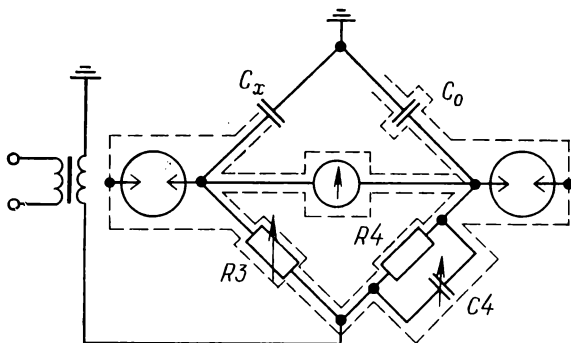


FIG. 3.3. Circuit diagram of a high-voltage bridge for measuring C_x and $\tan \delta$ of specimens with a grounded electrode

R_3 and C_4 are isolated from the high-voltage transformer terminal by capacitors C_0 and C_x ; the two resistive arms with the grounded junction are kept at low potential and, besides, connected to dischargers to guard them against a voltage surge in case of the specimen breakdown.

The inverted measuring circuit (Fig. 3.3) contains R_4 and C_4 connected in parallel as does the bridge circuit discussed above. This bridge is used where the object under test has a dead-grounded electrode (an insulator flange, cable sheath, etc.); high voltage is applied to the junction of the two resistive arms. In this type of circuit, all elements such as resistors R_3 and R_4 , capacitor C_4 , coupling cables, and

other current carrying parts must have the insulation of high resistance (not below $1\text{ M}\Omega$ at a voltage of $1\,000\text{ V}$) to withstand high test voltages. In bridges with a nominal voltage up to 10 kV , the one-minute-test voltage for the

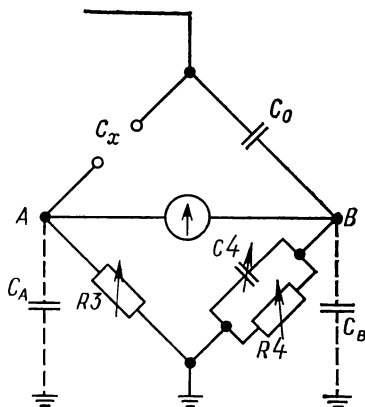


FIG. 3.4. Circuit diagram of a bridge showing stray capacitances

above elements is as high as 15 kV . The balancing of such circuits (adjustment of R_3 and C_4) is sometimes made at a distance by means of an insulating rod to safeguard the personnel against the danger of high-voltage stress.

The stray capacitances present in a bridge circuit cause in most cases a noticeable error in the measurement of $\tan \delta$. To compensate for these capacitances, it is customary to use either an auxiliary branch with adjustable resistors or an additional voltage source connected between the shield and ground. The value and phase of this guard voltage are so adjusted that the voltage across the stray capacitances becomes equal to zero. It is also possible to eliminate the effect of stray capacitances C_A and C_B (Fig. 3.4) by balancing the bridge twice at two fixed resistances R_3 and R'_3 .

According to balance equation (3.12), we define the condition characteristic of the first balancing with due regard for

the capacitances C_A and C_B :

$$\frac{-j \frac{1}{\omega C_0}}{1/R_3 + j\omega C_A} = \frac{1}{1/R_4 + j\omega (C_4 + C_B)} \cdot \frac{1}{g_x + j\omega C_x}$$

Equating the real terms in the left side and the right side of the equation, we obtain after cancelling out

$$-\omega^2 C_A C_0 = g_x/R_4 - \omega^2 C_4 C_x - \omega^2 C_B C_x$$

Whence, taking into account Eq. (3.3)

$$\tan \delta = \omega C_4 R_4 + \omega C_B R_4 - \omega \frac{C_A}{C_x} C_0 R_4$$

Substituting C into the above equation at $\tan \delta \leq 0.1$ gives

$$\tan \delta = \omega C_4 R_4 + \omega C_B R_4 - \omega C_A R_3 \quad (3.21)$$

Changing R_3 for R'_3 , we rebalance the bridge now at C'_4 and R'_4 . Here, at $\tan \delta \leq 0.1$,

$$\tan \delta = \omega C'_4 R'_4 + \omega C_B R'_4 - \omega C_A R'_3 \quad (3.22)$$

Using the last two equations, we have

$$\tan \delta = \omega C_4 R_4 - \frac{R_3}{R_3 - R'_3} (\omega C'_4 R'_4 - \omega C_4 R_4) \quad (3.23)$$

If R_3 and R'_3 are taken to be equal to $2R'_3$, formula (3.23) becomes simpler:

$$\tan \delta = \omega C_4 R_4 + 2\omega (C'_4 R'_4 - C_4 R_4) \quad (3.24)$$

The described principle underlies the operation of the type P525 high-voltage a.c. bridge designed to measure C_x and $\tan \delta$ of solid and liquid insulating materials at a frequency of 50 Hz (Fig. 3.5). This is a four-arm bridge whose one arm has a test specimen of capacitance C_x and the adjacent arm a standard capacitor of capacitance C_0 , which is an air capacitor of 100 pF rated at up to 10 kV. The other two arms mounted in the common casing include a box of nonreactive resistances $R3$ (up to 10 000 Ω), and a capacitance box $C4$ (up to 1 μ F). Since the resistor $R4$ with a resistance of $10^4/\pi\Omega$ is connected in parallel with the capacitance box $C4$, the value of $\tan \delta$ at 50 Hz will be equal in magnitude to the capacitance $C4$ measured in microfarads:

$$\tan \delta = \omega R_4 C_4 = 2\pi \times 50 \frac{10^4}{\pi} C_4 \times 10^{-6} = C_4$$

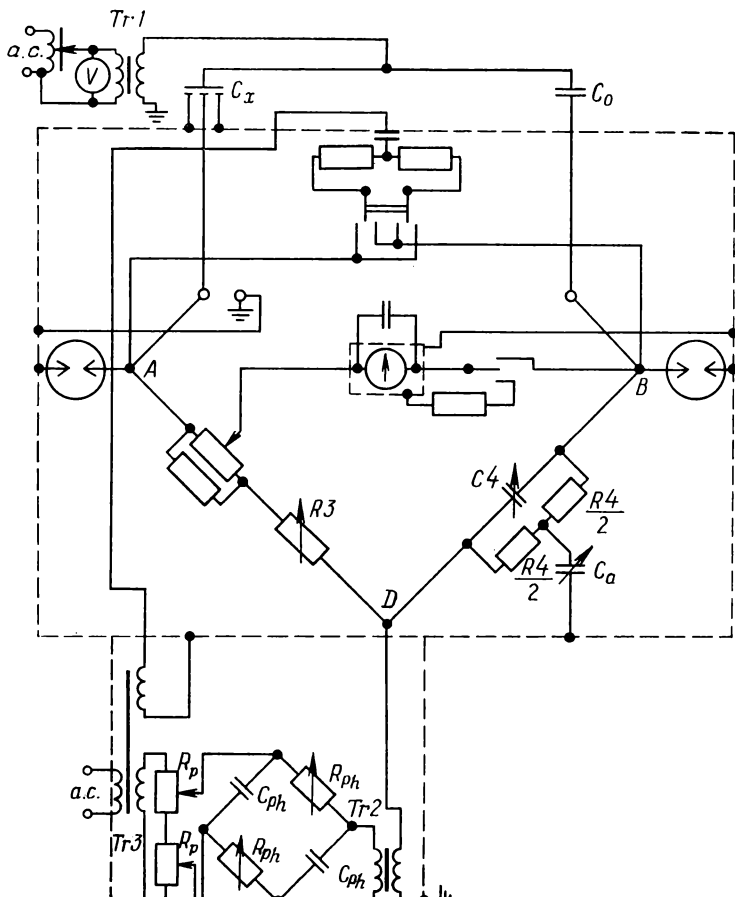


FIG. 3.5. Circuit diagram of a P525 bridge.

In other words, the values of $\tan \delta$ can be directly read on the scale of the capacitance box $C4$.

The bridge draws current from an a.c. supply line through an adjustable-ratio autotransformer and step-up transformer $Tr1$ with a transformation ratio of 100. The supply voltage is read on a voltmeter V inserted on the L. V. side, the transformation ratio being taken into account. It is advis-

able to apply voltages in the range from 3 to 10 kV, though measurements can also be taken at lower voltages starting from approximately 500 V. The voltage is applied to the junction of the capacitance arms directly from the transformer *Tr1* and to the junction of the resistance arms through a guard voltage arrangement intended to adjust the voltage at a junction *D* with respect to the grounded shield. This adjustment is necessary for cancelling capacitive leakage currents which otherwise could introduce an error in bridge balancing due to voltage redistribution in the bridge circuit. The guard circuit keeps the guard voltage equal to the voltage drop across the resistor *R4* and 180° out of phase with this voltage difference. By this means, at point *B* the voltage to ground becomes equal to zero, thereby excluding the occurrence of leakage current. With the bridge set at balance, the voltage between junctions *A* and *B* does not appear, so that at the junction *A* the voltage to ground is also equal to zero. The guard circuit consists of an auxiliary low-power transformer *Tr3*, two resistors R_p which change the value of guard voltage, and a phase shifter. The voltage tapped off the resistors is impressed across the two junctions of a four-arm bridge in which adjacent arms contain capacitors C_{ph} and adjustable resistors R_{ph} for changing the guard voltage phase. The other two junctions are connected to the primary of transformer *Tr2* whose secondary is placed between the junction *D* and ground.

The variable capacitor of about 1 000-pF capacitance (C_a) serves to adjust the bridge, that is, to balance the residual capacitances in the circuit. The capacitive balance of the bridge is made by using a special circuit fed from an auxiliary transformer. This balancing renders the bridge ready for running a set of single-type tests.

The capacitance of an insulation specimen must be within 40 pF-0.02 μ F, in which case it is possible to measure a loss tangent from 10^4 to 1. The bridge must operate from a 50-Hz sinusoidal voltage source. The measuring set is designed to work at an air temperature of 10 to 30°C and humidity up to 80%. The basic error in capacitance at normal temperature is within $\pm 0.5\%$ (but not less than 5 pF), and the error in loss tangent within 0.015 at voltages from 3 to 10 kV. The voltage constant of a vibration galvanometer used

with an amplifier to adjust the bridge comes to 5×10^{-7} V/mm. The working voltage can be raised, if required, to 35 kV. In this case the standard air capacitor and the step-up transformer should be replaced, for example, by a P-55 capacitor and HOM-35 transformer rated at this voltage.

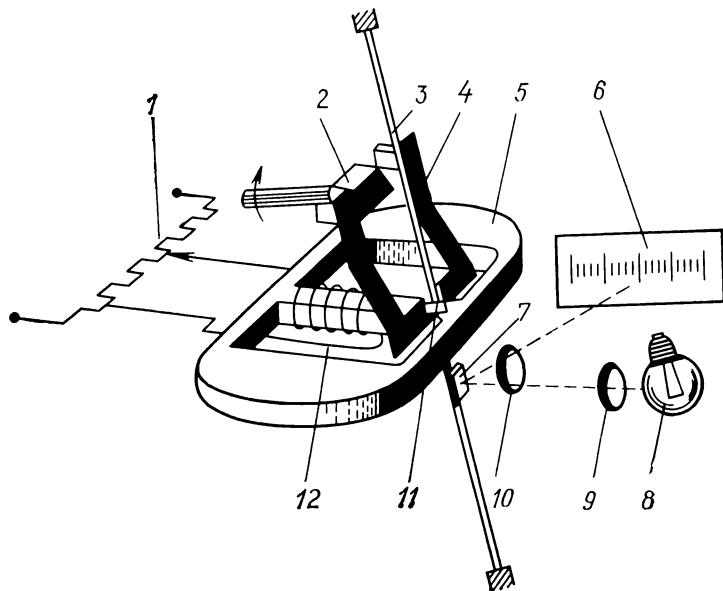


FIG. 3.6. Scheme of a vibration galvanometer

A vibration galvanometer (Fig. 3.6), which acts as a bridge balance (null) indicator, operates on the principle of interaction of a movable permanent magnet with an alternating magnetic field. This field is set up across a coil by the alternating voltage under measurement.

The movable magnet 11 is fastened to an aluminum plate held taut at both ends with thin bronze bands 3. Below the magnet, there is a mirror 7 attached to the plate. A beam of light travelling from lamp 8 through condenser lens 9 and objective lens 10 falls on the mirror, which reflects the light to produce a bright band on a galvanometer scale 6. The movable magnet is located in the gap between permal-

loy pieces 4, through which passes a magnetic flux from a stationary permanent magnet 2, and also in the gap formed between the pieces of an electromagnet whose magnetizing coil 12 draws an alternating current. The core 5 of the electromagnet is also made of permalloy.

With no current applied to the electromagnet coil, the movable magnet will set at zero under the influence of a counter torque. This torque arises from tensioning of the bronze bands and the effect of the permanent (static) field in the gap between the permalloy pieces, since this field extends along the axis of the movable magnet. The passage of an alternating current through the coil produces a magnetic field between the electromagnet pieces which extends at right angles to the axis of the permanent magnet set in the zero position. The alternating magnetic field causes vibration of the permanent magnet; the bright line on the scale that results from the reflection of the light beam by the mirror fixed to the movable magnet smears into a band whose width depends on the magnitude of alternating voltage being measured.

The swing that arises with the vibration of the permanent magnet is at a maximum when the natural frequency of the moving system coincides with the electrical frequency. To change the natural frequency of the moving system, that is, to tune it to resonance, the operator shifts the position of the permanent magnet 2 relative to the pieces 4 with a tuning knob and thus changes the amount of magnetic flux acting on the permanent magnet and also the magnetic component of the counter torque.

The magnetizing coil 12 is switched into the voltage measuring circuit through a voltage divider 1 which serves as a galvanometer sensitivity control. The galvanometer has a polarity reverser to change the direction of current flow and thus detect an interference, if any, in the measuring circuit. At the highest sensitivity, the galvanometer current constant is equal to 10^{-9} A/mm and the voltage constant to 2×10^{-5} V/mm. The galvanometer complete with an amplifier shows a yet higher sensitivity, so that its voltage constant can be equal to 5×10^{-7} V/mm.

Instead of a vibration galvanometer called upon to perform the function of a null indicator, one can use a high-

sensitivity selective transistor amplifier with a pointer instrument placed in the output circuit. The block diagram of such a balance indicator is shown in Fig. 3.7. The voltage across the opposite junctions of the bridge is fed to a preamplifier 1 which has a control device for adjusting the indica-

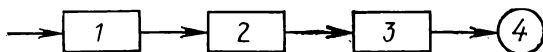


FIG. 3.7. Block diagram of an electronic null indicator

tor sensitivity. The output signal emerging from the preamplifier is routed to a selective amplifier 2 tuned to the frequency of the bridge supply voltage in order to amplify the signal of the basic frequency and suppress the noise signals whose frequency coincides with the supply voltage frequency. The amplifier's tuning frequency can be adjusted to match it to the frequency of the bridge supply source. The amplified signal is rectified by a phase-sensitive rectifier 3 and read by a moving-coil microammeter 4. The amplifier displays a log-log response; in other words, its sensitivity decreases with an increase in the value of an input signal. The highest sensitivity of such indicators comes to 1 mm/ μ V.

3.4. Calculation of Permittivity and Loss Tangent

As mentioned in Sec. 3.1, the permittivity ϵ of a specimen is calculated from the results of measurement of the specimen capacitance C_x between the electrodes of a measuring cell. Besides, it is necessary to measure or calculate the capacitance C_0 (vacuum capacitance) removing therewith the specimen from the circuit, but leaving the configuration of the electrodes intact.

Calculate the capacitance of a test specimen using the electrode system as shown in Fig. 1.1.

The effective electrode area is

$$F = \frac{\pi d_m^2}{4} = \frac{\pi (d_1 + g)^2}{4} \quad (3.25)$$

where d_1 is the diameter of a guarded electrode, and g is the gap between the guarded and guard electrode. Substituting Eq. (3.25) into Eq. (3.10), we obtain

$$C_0 = \epsilon_0 \frac{\pi (d_1 + g)^2}{4t} \quad (3.26)$$

Formula (3.26) does not consider field distortion at the edges of electrodes. Using a correction factor B to allow for

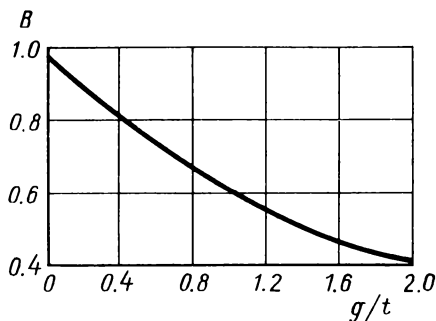


FIG. 3.8. Correction factor B to allow for field distortion at the edges of electrodes

field distortion, formula (3.26) takes the form

$$C_0 = \epsilon_0 \frac{\pi (d_1 + Bg)^2}{4t} = 0.0695 \frac{(d_1 + Bg)^2}{t} \quad (3.27)$$

The value of correction factor B depends on the gap g between the guarded and guard electrode, distance t between the guarded and high-voltage electrode, and electrode thickness a . With $a \ll t$, the correction factor can be determined from the graph of Fig. 3.8 or by the formula

$$B = 1 - 2.932 \frac{t}{g} \log \cosh \left(0.7854 \frac{g}{t} \right)$$

If $a > t$, field distortion at the edges of electrodes may be neglected, in which case $B = 1$.

For a tubular specimen (see Fig. 1.3), the interelectrode capacitance C_0 is calculated by the formula

$$C_0 = 0.2416 \frac{l + Bg}{\log (d_2/d_1)} \quad (3.28)$$

As noted earlier, the capacitance C_x of a specimen is taken to be the capacitance in its parallel equivalent circuit. If the instrument reads the capacitance representative of its series equivalent circuit, it is possible to convert from C_s to C_p

using the formula

$$C_p = \frac{C_s}{1 + \tan^2 \delta}$$

Knowing C_x and C_0 , we find ε with formula (3.11).

The loss tangent $\tan \delta$ can be read on the instrument's scale. If the scale is not graduated in terms of loss tangent, this can be calculated from the capacitance and resistance of a specimen in its parallel or series equivalent circuit by formulas (3.1) and (3.3).

Random errors are likely to appear when determining ε and $\tan \delta$. To exclude these errors, measurements are made several times. The number of measurements is specified in the standards on the materials and products. In testing liquid dielectrics, the difference between the results of separate measurements of $\tan \delta$ should not exceed 15%. For C_x , this scatter should lie within 5%. For solid materials, the allowable scatter in the measured values is set up in the standards. From the results of a series of test measurements we find the arithmetic mean of loss tangent and permittivity:

$$\overline{\tan \delta} = \frac{1}{n} \sum_{i=1}^n \tan \delta_i, \quad \bar{\varepsilon} = \frac{1}{n} \sum_{i=1}^n \varepsilon_i$$

where $\tan \delta_i$ and ε_i are the results of separate measurements; n is the number of measurements. The found arithmetic mean is taken as the final result of the tests.

The spread about the mean value may be described by the standard deviations for a group of n measurements. This error is found by the formula

$$S = \sqrt{\frac{1}{n-1} \sum_{i=1}^n \Delta_i^2}$$

where $\Delta_i = \varepsilon_i - \bar{\varepsilon}$ or $\Delta_i = \tan \delta_i - \overline{\tan \delta}$.

In estimating ε of liquid insulating materials, the vacuum capacitance C_0 is determined experimentally, that is, by measuring the capacitance of the empty cell. Then, filling the cell with the liquid under test, its capacitance C_x is measured using the same electrodes. With a three-electrode system employed for testing, stray capacitances may be disregarded, so that ε can be calculated with formula (3.11).

Where the measurements are carried out with a two-terminal cell or the permittivity should be determined to a high accuracy, we have to exclude from the results of both measurements the stray capacitance C_{str} caused by the presence of a solid dielectric, voids, and the capacitance of electrodes. To measure the stray capacitance C_{str} , the cell is filled with a standard liquid whose ϵ_{st} must be known to a sufficient accuracy and its $\tan \delta$ must be rather small. Standards recommend using the normal heptane as a standard liquid treated before tests with silica gel to remove moisture and oxidation products. The treated heptane has ϵ_{st} equal to 1.92 in the temperature range of 20 to 30°C. The measurements are made on the cell filled with air and then with the standard liquid to determine C_0 and C_{st} respectively. In both cases the measurement results include the stray capacitance C_{str} . The expression for ϵ_{st} thus takes the form

$$\epsilon_{st} = \frac{C_{st} - C_{str}}{C_0 - C_{str}} \quad (3.29)$$

from which we find the stray capacitance of the cell

$$C_{str} = \frac{C_0 \epsilon_{st} - C_{st}}{\epsilon_{st} - 1} \quad (3.30)$$

The permittivity of the liquid under test, ϵ_x , is computed by the formula

$$\epsilon_x = \frac{C_x - C_{str}}{C_0 - C_{str}} \quad (3.31)$$

To estimate the loss tangent of liquid materials, we must perform two sets of measurements, first, on the cell filled with air and, second, on the same cell filled with the test liquid, thereby determining $\tan \delta_0$ and $\tan \delta_1$ respectively. We find the sought-for value, taking into account the previous measurements, by the formulas:

for a three-terminal cell

$$\tan \delta = \tan \delta_1 - \frac{C_0}{C_x} \tan \delta_0 \quad (3.32)$$

for a two-terminal cell

$$\tan \delta = \left(\tan \delta_1 - \frac{C_0}{C_1} \tan \delta_0 \right) \frac{C_x}{C_x - C_{str}} \quad (3.33)$$

3.5. Safety Precautions

Since a.c. bridge circuits operate at high voltages it is essential to provide protection for the personnel engaged in the work on the electric equipment. In the first place, the design of a measuring unit should ensure reliable grounding of the components, proper insulation, and guarding of all exposed or partially exposed live parts against accidental contact with them.

The circuit diagram shown in Fig. 3.5 incorporates dischargers which protect control elements from excessive voltages if they appear in the circuit. It is seen from the figure that as the dischargers break down, the bridge junctions *A* and *B* become grounded.

The dischargers begin to glow as a result of rupture of a specimen, incorrect wiring, or insertion of too high a resistance R_3 in the circuit as against the resistance required for bridge balancing. As soon as the dischargers start glowing, the operator must disconnect the unit at once. The dischargers should be periodically checked for performance. In doing this, it is necessary to place in the circuit a protective resistor of about 2 000 Ω and determine the firing voltage; for a neon discharger of the CH-2 type this voltage is about 80 V. High-voltage cables should be periodically tested for insulation resistance, which shall be not below 10 M Ω . The entire circuit shall be grounded using copper wire 6 mm² in cross section. The high-voltage transformer that supplies power to the bridge, capacitor C_0 , and test specimen shall be placed in a test chamber or behind a metallic grounded guard to exclude contact with high-voltage leads and terminals. If the unit operates at 50 kV voltage, the guards should be at least 0.5 m distant from the parts subjected to high voltage. The chamber door (or guards) shall be furnished with an interlock to disconnect the supply circuit after opening the door. As with the high-voltage transformer frame, the shields of the bridge and of cable connections shall be properly grounded.

Each test station must have safety engineering instructions and keep a safety briefing log. Before being given permission to work on a measuring set, the workers must learn the instructions and sign in the log.

PERMITTIVITY AND LOSS ANGLE AT HIGH FREQUENCIES

4.1. General

Tests involved in the estimation of permittivity and loss tangent at frequencies above 100 Hz have some features associated with an increased effect of the fringing field, capacitance of a specimen relative to ground, and inductance and capacitance of current-carrying leads. Of much importance are also the initial internal parameters of measuring circuits. The use of special cells and measurement methods relying on double or even triple balancing of bridge circuits eliminates the above influences. Three-electrode cells can be employed, but since at frequencies of 1 000 Hz and over the guard rings do not produce the desired effect, it is common practice to resort to two-electrode systems with and without an additional movable electrode. Noncontact measuring systems are also in frequent use now.

The capacitance of a specimen is expressed in the following form:

$$C_x = C'_x - C_e - C_z \quad (4.1)$$

where C'_x , is the measured capacitance of the specimen; C_e is the edge a capacitance; and C_z is the capacitance of an electrode (ungrounded) with respect to ground.

The edge capacitance is estimated through graphic analysis proceeding from the geometrical dimensions of the specimen and electrodes. Formulas for the calculation of C_e are given in Sec. 4.7. In testing solid dielectric specimens shaped as tubes or making tests on liquid dielectrics in a cylindrical measuring cell, it is possible to cancel out the edge capacitance in the following manner. The capacitance of a specimen or liquid sample is measured twice using electrodes of various lengths. First, the capacitance C'_{x1} is noted, with a length l_1 of the first electrode, and then C'_{x2} is read off, with a length l_2 of the second electrode. In the

first and the second measurement the edge capacitance C_e will certainly remain invariable, while the self-capacitances C_{x1} and C_{x2} will be different in magnitude:

$$C'_{x1} = C_{x1} + C_e, \quad C'_{x2} = C_{x2} + C_e$$

The actual capacitance corresponding to the tube portion of length $l_2 - l_1$ will be represented as the difference $C_x = C'_{x2} - C'_{x1}$

The electrode capacitance C_z to ground must be determined by direct measurements. It is also possible to calculate the capacitance C_z by the method of electrical images. This method enables us to ascertain that a disc of diameter d can be changed for an equivalent sphere with the same electric flux, but having a diameter $D = d/\pi$. In this case the capacitance of the disc can be expressed as the capacitance of the equivalent sphere. The capacitance of the sphere is

$$C_z = 2\pi\epsilon\epsilon_0 D$$

Substituting the expression for D into the above formula and considering that $\epsilon_0 = 8.854 \times 10^{-12}$ F/m and ϵ of the air is equal to unity, we find the electrode capacitance to ground

$$C_z = \frac{2\pi \times 8.854 \times 10^{-12} d}{\pi} \approx 17.7 \times 10^{-12} d$$

If the diameter d is expressed in meters, we obtain the capacitance in farads.

4.2. Specimens and Electrodes

The permittivity ϵ and $\tan \delta$ of solid dielectrics in the frequency range from 100 to 5×10^6 Hz are determined on specimens having the shape of round or square plates or tubes. The diameter or width of a plate shall be equal to 25-150 mm, and the length of a tubular specimen 100-300 mm. The ratio of the diameter of a specimen to its thickness shall be not less than 10. Where the permittivity ϵ of the material under test is expected to be high (over 30), it is permissible to use specimens of a smaller diameter, but not less than 10 mm.

The dimensions of a specimen must always be chosen such that, in conformity with the expected value of ϵ , its capaci-

tance shall be within the limits stipulated in the instructions on the measuring set and can be measured accurate to 1%. This capacitance covers the range from 100 to 500 pF.

The surface of a specimen shall be smooth and even, without dents, fissures, and scratches. The material shall be free of foreign substances. Its surface may be cleaned, of necessity, with a solvent that does not affect the material properties.

The geometrical dimensions of a specimen must be measured accurate to $\pm 0.5\%$.

The specimen thickness is defined as the arithmetic mean of the results of measurements taken at least at five points evenly spaced on the specimen surface. Each of the measured values shall not depart from the arithmetic mean by more than 5% for specimens less than 0.5 mm thick, and more than 2% for specimens 0.5 mm thick and above.

As stated earlier, it is permissible to use a two-electrode or three-electrode system depending on the measuring devices employed for the purpose.

In a three-electrode system (see Fig. 1.1), the diameter of a guarded electrode is chosen from the column of diameters given in Table 1.1. The concrete value of a diameter must be indicated in the standard or specifications on the material. The width of a guard electrode shall be at least twice the specimen thickness, but not less than 10 mm. The gap between the guarded and the guard electrode should be as small as possible, the upper permissible limit being 2 mm. The diameter of a high-voltage electrode shall be equal to the outer diameter of a guard electrode.

For tubular specimens, the width of a high electrode ranges from 75 to 300 mm and that of a guard electrode comes to at least 10 mm.

In a two-electrode system, the electrodes shall have the same dimensions as in a three-electrode system. The electrodes here may extend to the outer edge of the specimen or terminate a little short of the edge. The manner in which the electrodes are positioned on specimens is illustrated in Fig. 4.1.

If the area of electrodes is equal to or less than the area of the specimen (Fig. 4.1*b, d*), the distance from the electrode edge to the specimen edge shall be at least twice the thick-

ness of the specimen. Where the electrodes differ in diameter, the larger diameter shall exceed the smaller diameter by at least twice the thickness of the specimen.

Tin, lead, or aluminum foil 10 to 50 μm thick may serve as the electrode material. Foil is coated with a thin layer of chemically pure petrolatum, capacitor oil, or any other

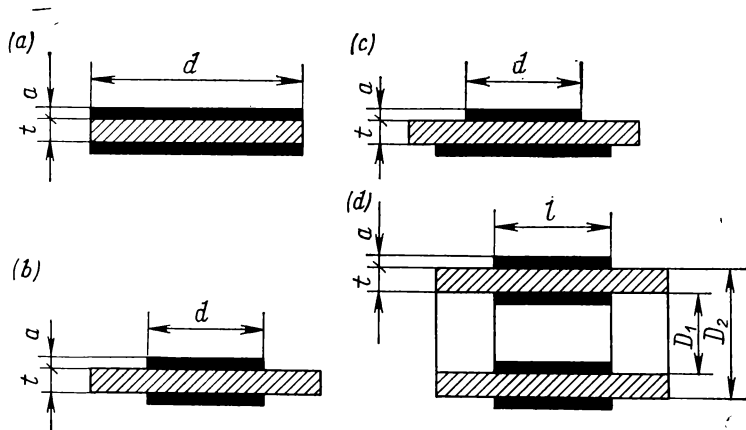


FIG. 4.1. Arrangement of electrodes on a specimen

(a) electrodes whose area is equal to the area of specimen; (b) and (c) electrodes whose area is less than the area of specimen; (d) tubular electrodes

similar substance showing a small dielectric loss ($\tan \delta < 3 \times 10^{-4}$). The foil is then pressed on the specimen and thoroughly rolled over to remove the excess grease and to obtain a tight bond without air inclusions. One must see that the adhesive does not get on to the edge and to the end face of the specimen. For ceramics, mica, glass, and similar dielectrics, it is customary to employ electrode films from silver, zinc, or aluminum deposited on the surface of a specimen by the fusion (firing) method considered earlier; the firing process is repeated twice to obtain a more uniform film. If the temperature required for the process proves excessively high for a given insulation specimen, recourse is made to cathode sputtering or vacuum evaporation. The deposited layer of metal should be uniform, 5 to 10 μm thick.

Foil and film electrodes are suitable for both flat and tubular specimens. It is advisable to produce an electrode on the

inside of tubular specimens only by metal deposition.

Where a method of metal deposition or deposited electrodes themselves have an adverse effect on the properties of a material, or where the need arises to cut off the time of

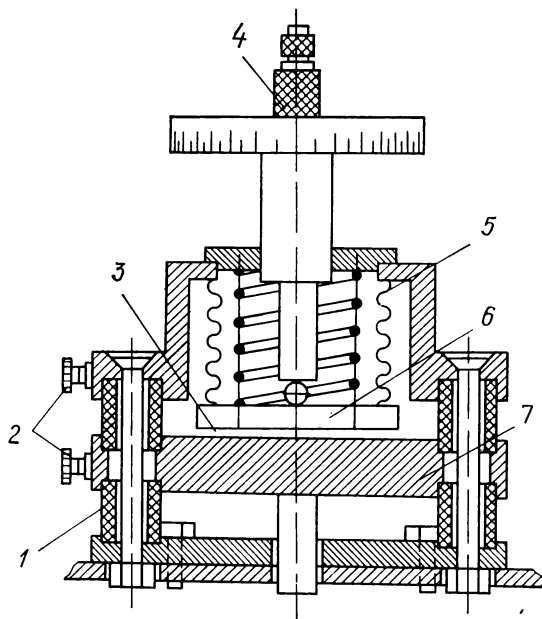


FIG. 4.2. Micrometer-electrode cell. Schematic

testing, it is well to employ clamped electrodes from steel, nonferrous or noble metals, or electrodes from conductive rubber. Conductive rubber electrodes should be dimensioned to a very high degree of accuracy. Because they are inherently high-resistive, these electrodes are only applicable over the low-frequency range. Conductive pastes and varnishes can also serve as electrode materials.

While making a choice of the electrode type, it should be first of all kept in mind that the method of electrode deposition must not affect the physicochemical or electrical properties of the materials being tested. Test specimens should be

kept free from contaminants. The dimensions of electrodes should be measured accurate to $\pm (0.005 L + 0.1)$ mm, where L is the linear dimension of the electrode.

The clamping devices for electrodes employed in the frequency range up to 1 MHz are of the lever, screw, or spring types. The pressure an electrode exerts on the specimen should be equal to 10 ± 2 kPa.

The use of a micrometer-electrode system (Fig. 4.2) is advisable above 0.1 MHz and obligatory above 1 MHz. In this system, the measuring cell consists of two electrodes, one being stationary (7) and the other movable (6). The stationary electrode is isolated from other elements of the cell with fused quartz insulators 1. A test specimen is located in a space 3 between the stationary and the movable electrode. The movable electrode is pressed against a specimen with a micrometer screw 4 and bellows 5. Terminals 2 serve for connection of the cell to the measuring circuit.

Before taking measurements, a specimen is placed between the micrometer electrodes and then the micrometer screw is driven well home to clamp the specimen between the electrode plates. The interelectrode spacing is read on the micrometer to within $\pm 1\%$. If the specimen is provided with foil or deposited electrodes, the thickness of the electrodes is subtracted from the distance read off on the micrometer dial. The micrometer screw has a ratchet with a spiral spring to keep the specimen under constant pressure.

Tests on liquid dielectrics are made in a cell described in Sec. 1.3 (see Fig. 1.10).

4.3. Bridge Methods. Measurement of C and $\tan \delta$

The capacitance and loss tangent of materials in the frequency range up to a few kilohertz are commonly measured with bridge methods. The bridge circuits and methods used allow for the compensation of stray capacitances and inductances which can cause considerable error in the results of measurement over the frequency range mentioned above. One of the basic approaches employed to exclude the effect of stray capacitances and inductances is double balancing of the bridge (the substitution method of measurement).

First the bridge is balanced with the test specimen connected to the circuit, then the bridge is rebalanced with the specimen disconnected.

Among the bridge circuits used in practice, we can single out two groups: capacitance bridges and inductive-arm (transformer coupled) bridges.

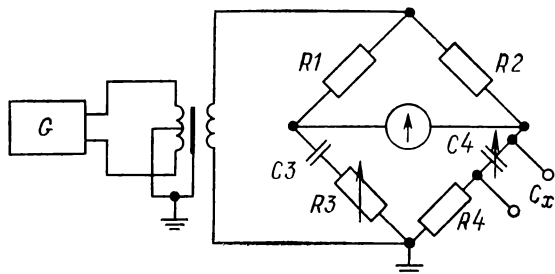


FIG. 4.3. Circuit diagram of a capacitance bridge with variable C and R

Capacitance bridges. To this group belong four-arm bridges whose arms contain only resistive and capacitive elements. Fig. 4.3 shows one such bridge circuit which has equal-ratio resistance arms with nonreactive resistors $R1$ and $R2$, replaceable capacitors $C3$ and $C4$, a fixed resistor $R4$ and variable resistor $R3$. The power loss in capacitors should be negligible. A test specimen is connected in parallel with the capacitor $C4$ and the bridge is balanced by adjusting the parameters of elements $C4$ and $R3$, keeping the capacitance of $C4$ to a minimum. If, despite the trial, the capacitance grows high, the capacitor $C3$ should be changed for another of higher capacitance. Let the balance be made at the capacitance C'_4 and resistance R'_3 . With the specimen disconnected, the second balance is taken, now at the capacitance C''_4 and resistance R''_3 .

To derive calculation formulas, let us represent the specimen by a parallel equivalent circuit (C_x in parallel with R_x) and obtain an expression for the specimen impedance shunted by the capacitance C'_4

$$Z_0 = \frac{R_x [1 - j\omega R_x (C'_4 + C_x)]}{1 + [\omega R_x (C'_4 + C_x)]^2} \quad (4.2)$$

Find the first-balance equation from the equality of the products of impedances in the opposite arms:

$$R_1 \left\{ \frac{R_x - j\omega R_x^2 (C'_4 + C_x)}{1 + [\omega R_x (C'_4 + C_x)]^2} + R_4 \right\} = R_2 \left(R'_3 - j \frac{1}{\omega C_3} \right) \quad (4.3)$$

The rebalance (second-balance) equation is

$$R_1 \left(R_4 - j \frac{1}{\omega C'_4} \right) = R_2 \left(R''_3 - j \frac{1}{\omega C_3} \right) \quad (4.4)$$

Equating the real and imaginary terms and considering that $R_1 = R_2$, we obtain from the above equation

$$R_4 = R''_3, \quad C_3 = C''_4 \quad (4.5)$$

Substituting these values into Eq. (4.3), we find real components of the equation

$$\frac{R_x}{1 + [\omega R_x (C'_4 + C_x)]^2} + R''_3 = R'_3 \quad (4.6)$$

and imaginary components

$$\frac{\omega R_x^2 (C'_4 + C_x)}{1 + [\omega R_x (C'_4 + C_x)]^2} = \frac{1}{\omega C''_4} \quad (4.7)$$

We can determine the specimen capacitance taking into account the fact that if C_4 is invariable, then the capacitance ($C'_3 + C_x$) in the adjacent arm with the bridge set at balance must be equal to the capacitance C''_4 with the bridge rebalanced. Hence

$$C_x = C''_4 - C'_4 \quad (4.8)$$

Transforming Eq. (4.6), we get

$$R_x = (R'_3 - R''_3) [1 + \omega^2 R_x^2 (C'_4 + C_x)^2]$$

Substituting R_x into Eq. 4.7 with regard to Eq. (4.8) gives

$$\omega R_x C''_4 (R'_3 - R''_3) = \frac{1}{\omega C''_4} \quad (4.9)$$

Substituting C_x given by Eq. (4.8) and R_x from Eq. (4.9) into expression (3.4), we find the dissipation factor:

$$\tan \delta = \frac{1}{\omega C_x R_x} = \frac{\omega (C''_4)^2 (R'_3 - R''_3) 10^{-12}}{C''_4 - C'_4} \quad (4.10)$$

where capacitances C'_4 and C''_4 are expressed in picofarads.

The elements of the measuring set must meet a number of requirements. The generator g shall offer the stability in frequency read on the scale to an accuracy better than $\pm 1\%$.

The input transformer shall be shielded and balanced to ground, the transformation ratio being taken to equal 4 to 10. Each of the resistances R_1 and R_2 of nonreactive resistors comes to 5 000 Ω . The variable capacitor C_4 has $\tan \delta < 10^4$ with the capacitance adjustable from 50 to

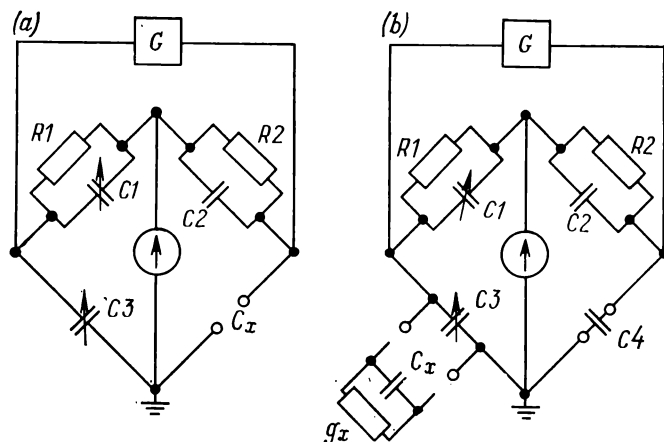


FIG. 4.4. Circuit diagram of a capacitance bridge with variable capacitors

(a) direct method; (b) substitution method

1 500 pF; the error in capacitance read on the vernier shall be kept within ± 0.2 pF. The variable resistor R_3 is a decade resistance box adjustable in decade steps from 1 to 10 000 Ω . All the components of the bridge shall be reliably shielded, the shields grounded. Also, the components shall be symmetrical with respect to ground.

The error in ϵ determined with the use of this balanced bridge comes to $\pm 2\%$ and in $\tan \delta \leq 0.01$ to $\pm 5\%$.

Another bridge circuit (Fig. 4.4) with fixed resistors has an advantage in that it does not use a variable standard resistor. The bridge arms contain fixed resistors R_1 and R_2 , a fixed capacitor C_2 , and variable capacitors C_1 and C_3 . Measurements are made by both the direct and the substitution method. In the direct method (Fig. 4.4a), a specimen of capacitance C_x is placed in the arm as shown in the figure

and the bridge is balanced by adjusting the capacitances of C_3 and C_1 . The sought-for values are found from Eqs. (3.16) and (3.17).

$$C_x = C_3 \frac{R_1}{R_2}, \quad \tan \delta = R_1 \omega C_1 \quad (4.11)$$

The expression for $\tan \delta$ shows that the scale of C_1 can be laid out in units of $\tan \delta$ because the frequency ω and resistance R_1 are invariable.

In the substitution method (Fig. 4.4b), a capacitor C_4 is connected in one of the arms as shown in the figure with the specimen disconnected; the capacitor must have higher capacitance than the specimen.

The balance is secured at some values C'_3 and C'_1 . Since the scale of C_1 is calibrated to read dissipation factor directly, we in essence have to note C'_3 and $\tan \delta'$:

$$\tan \delta' = \omega C'_1 R_1 \quad (4.12)$$

Connecting the specimen having parameters g_x and C_x in parallel with the capacitor C_3 , a second balance is effected, now at new values C''_3 and $\tan \delta''$:

$$\tan \delta'' = \omega C''_1 R_1 \quad (4.13)$$

The sought-for parameters are expressed in the form

$$C_x = C'_3 - C''_3 \quad (4.14)$$

$$\tan \delta = C'_3 \frac{\tan \delta'' - \tan \delta'}{C_x} \quad (4.15)$$

The frequency of the power source must be kept stable during measurements because it enters into the formulas for $\tan \delta$.

A third bridge circuit (Fig. 4.5) containing fixed capacitances does not require for its assembly variable capacitors with precision scales. The variable elements here are resistance boxes. This type of bridge can also read directly the measured quantities. The circuit includes variable resistors R_1 and R_3 which serve for bridge balancing with respect to the active and reactive components of voltage; as shown below, the scale of R_1 can be laid out in terms of C_x and the scale of R_3 in $\tan \delta$.

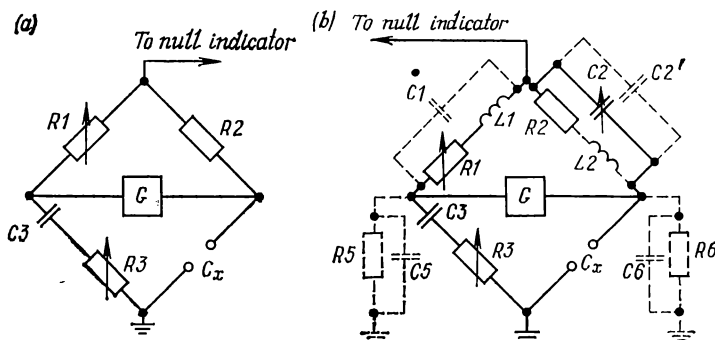


FIG. 4.5. Circuit diagram of a capacitance bridge with variable resistors

(a) circuit diagram; (b) circuit showing stray capacitances and resistances

Resistor R_2 is an invariable element, which should be changed for another on passing to the next range of measurement.

The bridge is at balance if

$$Z_1 Z_x = Z_2 Z_3$$

For the series equivalent circuit of the specimen, we get

$$R_1 \left(R_s - j \frac{1}{\omega C_s} \right) = R_2 \left(R_3 - j \frac{1}{\omega C_3} \right)$$

Equating the real parts gives

$$R_s = R_3 \frac{R_2}{R_1}$$

and doing the same for the imaginary terms, we have

$$C_s = C_3 R_1 / R_2, \quad \tan \delta_x = \omega C_3 R_3 \quad (4.16)$$

From these equations it follows that with R_2 and C_3 being constant, the scale of R_1 can be calibrated directly in capacitance, because, according to formula (3.6), at low loss angles ($C_s = C_x$) the scale of R_3 can be calibrated to read dissipation factor directly.

In reality, however, the circuit is not free from stray capacitances, inductances, and conductances whose effect causes additional errors which become noticeable even in the audio frequency range (Fig. 4.5b). Since the capacitance C_1

and inductance L_1 affect the accuracy of loss angle measurement, it is useful to employ a nonreactive resistor $R1$ and appropriate means to decrease the self-capacitance C_1 of the resistor. To compensate for the inductance L_2 , a noncalibrated trimmer $C2$ is connected across $R2$. Stray capaci-

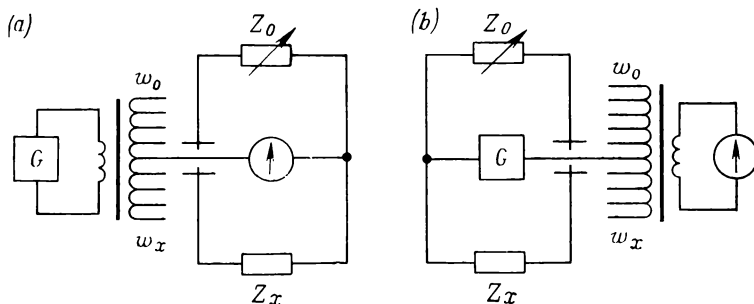


FIG. 4.6. Transformer bridges

(a) inductive coupling in feed circuit; (b) inductive coupling in null-detector circuit

tances C_5 and C_6 and also resistances R_5 and R_6 arise from the effect of the measuring unit elements and the transformer. For this reason the measuring set usually incorporates a special doubly shielded transformer and also has insulation parts made from high-quality materials such as polystyrene and polytetrafluoroethylene to decrease the effect of capacitance and conductance. As in other bridges, the source here is a rather high-power audio-frequency generator with a balanced output circuit whose output voltage is $U \geq 100$ V. The bridge can use a null indicator consisting of a CRT and an amplifier or another device of an input resistance not below 220 k Ω , provided with a sensitivity control for setting the bridge to balance.

Transformer bridges. In the last years transformer coupled bridges have become popular, in which the transformer secondary supplies power to the bridge and at the same time forms a pair of its arms (Fig. 4.6a). It is also quite possible to interchange the positions of the indicator and the supply (Fig. 4.6b). Such a bridge with inductively-coupled arms in the indicator circuit has a number of advantages. It offers a high sensitivity as to capacitance and dissipation factor;

in this case the hysteretical behavior of the transformer core and the nonlinearity of the magnetization curve do not affect the sensitivity. Besides, stray conductances inserted across the inductive arms are also of little significance. Last, the use of multitap transformers permits extending the range of measurement. There are a few varieties of transformer bridges. The first condition of balance for a bridge with inductive-coupled arms in the indicator circuit has the form

$$C_x/C_0 = w_0/w_x \quad (4.17)$$

where w_x and w_0 are the number of turns in the winding sections adjacent to C_x and C_0 respectively. The second condition of balance (as to conductance) can be met directly by varying the conductance in the arm Z_0 . In this case

$$\tan \delta = \tan \delta_0 \quad (4.18)$$

A double transformer bridge (Fig. 4.7) has found extensive use. It offers certain advantages over the bridge circuits considered above. First it should be noted that the circuit can be set at complete balance by switching over the turns of the arm elements, without using variable resistors and capacitors. This is an important feature since the use of tapped transformers enables us to extend the measuring range of instruments and decrease the number of reference standards. Resistive decoupling of circuits ensures good noise immunity and thus makes it easier to protect the bridges against the effect of stray couplings and allows connecting the object under test to the instrument with long wires.

The balance equation for the bridge (Fig. 4.7a) is

$$\frac{Z_x}{Z_0} = \frac{w_1 w_3}{w_2 w_4} \quad (4.19)$$

The circuit diagram shown in Fig. 4.7b offers separate and direct readout of capacitance and dissipation factor. The balance condition for this circuit has the form

$$C_x = C_0 \frac{w_2 w_4}{w_1 w_3} \quad (4.20)$$

$$\tan \delta_x = \frac{1}{\omega R_0 C_0} \frac{w_5}{w_4} \quad (4.21)$$

The capacitive balance of the bridge circuit is made by connecting the required number of winding turns w_2 ; to secure the loss tangent balance requires connecting of the appropriate number of winding turns w_5 . The number of turns w_4 must remain constant.

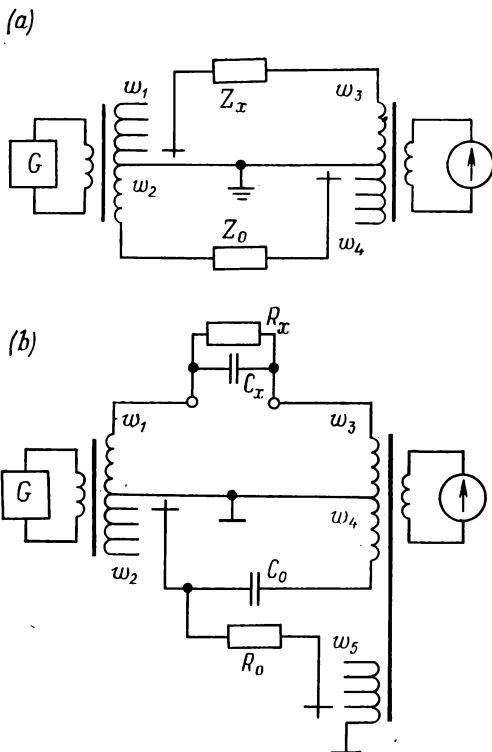


FIG. 4.7. Transformer bridges

(a) circuit diagram; (b) circuit diagram of bridge with separate balancing

Shielding of bridge circuits. The use of bridge circuits at high frequencies is only possible on condition that thorough shielding and preliminary balancing are secured to eliminate the effect of stray capacitances and internal inductances of the bridge elements. Four-arm bridge circuits used for testing materials in the frequency range from 1 to 100 MHz

include both inductive-arm and noninductive (capacitance-resistance) types.

Thoroughly shielded bridges whose arms contain only resistors and capacitors often find use for work at high

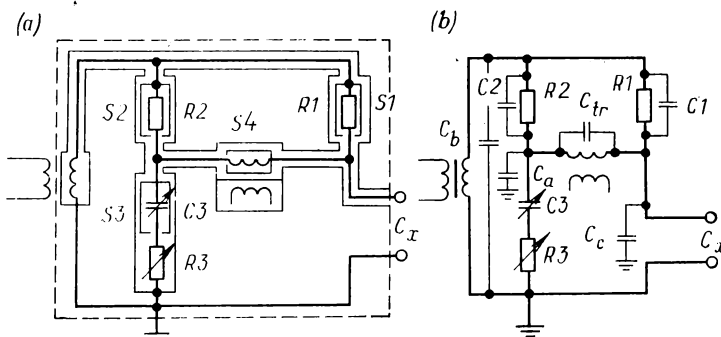


FIG. 4.8. Circuit diagram of a capacitance bridge

(a) shielded bridge circuit; (b) unshielded bridge circuit showing stray capacitances of circuit elements

frequencies. Double shielding of an ungrounded part of the circuit and its individual elements (Fig. 4.8) protects the bridge against external influences and keeps stray capacitances constant. Additional shields also ensure an invariable character of stray capacitance coupling.

The shields of resistors R_1 and R_2 determine the capacitances of capacitors C_1 and C_2 . In the identical design of arms, the ratio between the resistances of resistors R_1 and R_2 is independent of stray capacitances. The capacitances between shields S_1 , S_4 , and ground represent a capacitance C_b placed in parallel with the source; the capacitance between a shield S_3 and ground is C_a ; the capacitance of S_4 is C_c ; and the capacitance of the transformer winding is C_{tr} . In this bridge circuit, a sine-wave generator may serve as a power supply, and a pointer instrument coupled to an amplifier with a high-resistance input as a balance indicator.

It is expedient to measure C_x and $\tan \delta$ by the method of double balancing; C_3 and R_3 should have scales graduated in picofarads and ohms respectively. First a no-loss capacitor C_4 is connected to terminals (C_x) and a specimen is inserted in parallel with the capacitor. Balance is now effec-

ted by adjusting the parameters of R_3 and C_3 , the capacitor C_3 being adjusted to have the highest possible capacitance. If it is impossible to secure the balance at this condition, C_4 should be changed for another capacitor to set the bridge at balance. Assume that at the first balance we have R'_3 and C'_3 and at the second balance, with the specimen removed, we obtain C''_3 (R''_3 is obviously equal to zero).

Let us represent the specimen as a parallel equivalent circuit (C_x in parallel with R_x). Finding the impedance of the specimen shunted by the capacitor C_4 , in analogy to Eq. (4.3) we write the equation for the first balance of the bridge:

$$R_2 \left\{ R_x \frac{1 - j\omega R_x (C_4 + C_x)}{1 + [\omega R_x (C_4 + C_x)]^2} \right\} = R_1 \left\{ R'_3 - j \frac{1}{\omega C'_3} \right\} \quad (4.22)$$

The equation for the second balance takes the form

$$R_1 \left(-j \frac{1}{\omega C''_3} \right) = R_2 \left(-j \frac{1}{\omega C_4} \right) \quad (4.23)$$

Considering that $R_1 = R_2$ and, at low power loss in the specimen,

$$C'_3 = C_4 + C_x \quad (4.24)$$

we find, taking account of Eq. (4.23),

$$C'_3 = C''_3 + C_x \quad (4.25)$$

Comparing the real parts of Eq. (4.22), having regard to Eq. (4.24), we obtain

$$R_x = \frac{1}{\omega^2 R'_3 (C'_3)^2} \quad (4.26)$$

Now we find the unknowns (the capacitance here is in picofarads):

$$C_x = C'_3 - C''_3 \quad (4.27)$$

$$\tan \delta = \frac{1}{\omega R_x C_x} = \frac{\omega R'_3 (C'_3)^2}{C'_3 - C''_3} 10^{-12} \quad (4.28)$$

4.4. Bridge Elements and A.C. Bridges

Alternating current bridges are commercially available in many types and classes. In some cases, the specifics of tests necessitate constructing a bridge from separate units and components. These are resistance and capacitance boxes, in-

strument resistors and capacitors, sinusoidal-voltage audio-frequency and radio-frequency generators, and null indicators. Consider in brief the arrangement and characteristics of these elements.

Null indicators. These detectors of bridge balance comprise an amplifier connected across a pair of opposite bridge junctions and a pointer instrument or cathode-ray tube

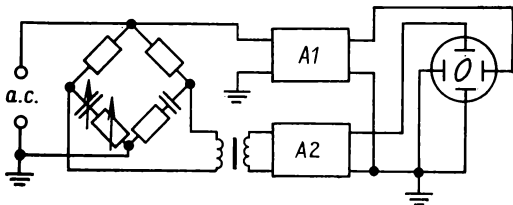


FIG. 4.9. Connection diagram of a CRT null indicator

placed at the output. The block diagram of a balance indicator with a pointer instrument was discussed in Sec. 3.3.

Figure 4.9 shows the circuit diagram of a CRT null indicator. As seen, the bridge source voltage U_1 is applied to the tube's horizontal deflection plates through an amplifier $A1$. The voltage U_2 across a pair of the opposite junctions of the bridge is applied to the vertical deflection plates through a transformer and an amplifier $A2$. If the bridge stays unbalanced, the voltages U_1 and U_2 are out of phase and the screen displays a visible pattern in the form of an ellipse. If we secure a balance with respect to the reactive component, the ellipse changes into a straight inclined line. Setting the bridge at balance with respect to the active component too ($U_2 = 0$) causes the straight line to occupy a horizontal position. Thus the image on the screen shows how we must balance the bridge, either relative to the reactive or to the active component. The sensitivity of the null indicator depends on the CRT sensitivity and the gain factor which has the largest value only at a definite frequency. In some devices this frequency can be changed in a stepwise manner with a special filter. The amplifier gain is possible to control.

The Soviet industry puts out CRT balance indicators complete with a power unit, Y- and X-amplifiers, and an

input transformer. The Y -amplifier incorporates an RC filter with step-by-step adjustment to obtain the highest gain at a definite frequency.

Sinusoidal generators. A sinusoidal generator used to feed power to a bridge circuit must meet certain requirements. First of all it must generate sinusoidal voltage of the desired frequency and stable amplitude. The instability of the sine-wave amplitude shall be kept within $\pm 3\%$, and the stability in frequency shall be such that its drift over the measurement period be below 1% of the frequency rating. The basic error in frequency setting shall be within $\pm 1\%$. Provision shall be made for a smooth regulation of the a.c. voltage and its frequency. The output power of the generator shall be sufficient for proper performance of the bridge circuit. It should be remembered that if its output power is not high enough, the generator runs at overload, which leads to a nonlinear distortion in the output voltage waveform. When making a choice of the generator or developing a bridge circuit, one must see that the equivalent resistance of the circuit matches the rated load on the generator.

Table 4.1 lists some characteristics of the commercially available generators.

TABLE 4.1

Audio Signal Generators

Type	Frequency range, Hz	Frequency setting error, Hz	Output power, W	Max. output voltage, V	Output resistance, Ω	Nonlinear distortion factor, %
$\Gamma 3-102$	$20-2 \times 10^5$	$0.01f + 0.2$	—	8	600	0.02-0.2
$\Gamma 3-104$	$20-40 \times 10^3$	$0.01f + 2$	1.5	30	5, 50, 600	1
$\Gamma 3-105$	$10-2 \times 10^6$	$\pm 5 \times 10^{-7} f$	—	1	50	2-5

Resistance boxes. Laboratories that work out bridge circuits often use resistance boxes and separate instrument resistors, the latter being made in the form of a wound coil from manganin wire or thin tape. The resistor has two current terminals to connect it to the current circuit and one more pair of terminals for connection to the voltage circuit. At frequencies of the order of 1 000 Hz the self-capacit-

ance C_0 and inductance L_0 of the resistor begin to affect the performance of the bridge.

The equivalent circuit for a resistor with lumped parameters may be represented as R and L_0 connected in series and shunted by the capacitance C_0 .

The impedance of this circuit is

$$Z = \frac{-j \frac{1}{\omega C_0} (R + j\omega L_0)}{-j \frac{1}{\omega C_0} + R + j\omega L_0}$$

After performing transformations, we get

$$Z = \frac{-j (R + j\omega L_0) [R\omega C_0 - j (\omega^2 L_0 C_0 - 1)]}{R^2 \omega^2 C_0^2 + (\omega^2 L_0 C_0 - 1)^2}$$

The frequency ω is commonly much lower than the natural resonance frequency ω_0 specified by the condition

$$\omega_0 L_0 = \frac{1}{\omega_0 C_0}$$

In this case the following inequality holds

$$\omega^2 L_0 C_0 \ll 1$$

so that the network impedance is

$$Z = \frac{(\omega L_0 - jR) (R\omega C_0 + j)}{R^2 \omega^2 C_0^2 + 1} = \frac{R (1 + \omega^2 L_0 C_0) + j (\omega L_0 - R^2 \omega C_0)}{R^2 \omega^2 C_0^2 + 1} \approx \frac{R + j\omega (L_0 - R^2 C_0)}{R^2 \omega^2 C_0^2 + 1}$$

The time constant

$$\tau = \frac{L_0 - R^2 C_0}{R}$$

characterizes the effect of self-capacitance C_0 and self-inductance L_0 on the frequency response. The smaller the time constant of the equivalent impedance Z , the more comparable the resistor becomes to the ideal nonreactive resistor in parameters. The inductance and capacitance of a resistor can be decreased in a number of ways: by employing special types of coil winding, sectionalizing, and using forms made from thin plates of mica, plastics, and other materials.

Resistors come in various resistance ratings, from 10^{-5} to $10^{10} \Omega$. The error in d.c. resistance lies within $\pm(0.005$ to $0.05)\%$ depending on the resistance rating of resistors, and

the error in a.c. resistance within $\pm(0.02 \text{ to } 0.05)\%$. Over the resistance range from 1 to 10 Ω , the time constant is $\tau = 5 \times 10^{-9}$ s; at $R = 10^5 \Omega$, $\tau = 2.5 \times 10^{-6}$ s. The temperature coefficient of resistance does not exceed $5 \times 10^{-5} \text{ K}^{-1}$.

A resistance box consists of a set of resistors of various ratings, which can be connected in series with each other. By the means of switching, resistance boxes are divided into plug, dial, clamp, and fork types.

In plug-type resistance boxes, the terminals of resistors are connected to brass plates having semispherical sockets. Inserting plugs into sockets shorts out the terminals of resistors. The type P-58 box, for example, contains 24 resistors rated at 0.1 to 40 000 Ω . Using plugs, we can change the value of total resistance from 0.1 to 111 111 Ω in 0.1 Ω steps. The initial resistance of the box, $R_0 = 0.02 \Omega$. The box is designed for work at frequencies up to 10 kHz. The deviation of resistances from the nominal values is within $\pm(0.002R + 0.004) \Omega$ at 1 000 Hz. The permissible load on each resistor does not exceed 1 W at a current of 1 A.

Dial boxes have an assembly of resistance coils connected to corresponding contacts. On turning a dial selector switch, a slip brush slides along the contacts. The value of the resistance placed into the circuit is read by the position of the dial switch. Dial boxes contain a few sections (decades) of resistors. For example, the type P517M box consists of six decades of precision resistors: a decade includes 11 resistors each of the same resistance value. In the " $\times 0.01 \Omega$ " and " $\times 0.1 \Omega$ " decades the resistors are made coilless; in the other decades the resistors are bifilar coils. The box can be set to any desired value in the range from 0.01 to 12 222.21 Ω at a step of 0.01 Ω . The time constant ranges from 15×10^{-8} to 150×10^{-8} s depending on the manner of switching and the resistance being set up.

Capacitance boxes. Air and mica capacitors usually serve as capacitance standards.

An air capacitor is of the variable type. The capacitor consists of a system of movable and stationary plates. As the axle rotates the movable plates enter into the gaps between the stationary plates. The highest capacitance of an individual capacitor is not above 0.001 μF at an accuracy rating of

TABLE 4.2
A. C. Bridges

Type	Measuring range		Frequency, Hz	Measurement error	
	C, pF	tan δ		C, %	tan δ
P571	10^{-10}	$1 \times 10^{-3-2}$	$40 \cdot 5 \times 10^3$	$\pm(0.1 + 14/C_x)$	$\pm(0.05 \tan \delta + 5 \times 10^{-4})$
P589	$0.01 \cdot 10 \times 10^6$	$3 \times 10^{-4-0.1}$	1 000	$\pm(0.1 + 2/C_x)$	$\pm(0.02 \tan \delta + 5 \times 10^{-4})$
E7-4	10^{-10}	0.005-0.1	100, 1 000	$\pm(2 + 30/C_x)$	$\pm(0.1 \tan \delta + 5 \times 10^{-3})$
MJE-1	$10^2 \cdot 10^6$	$1 \times 10^{-4-0.5}$	$4 \times 10^2 \cdot 10^4$	± 0.2	$\pm(0.02 \tan \delta + 5 \times 10^{-4})$
F8-4	$0.03 \cdot 16 \times 10^6$	$(5 \cdot 999) \times 10^{-4}$	1 000	$\pm(0.1 + 2/C_x)$	$\pm(0.02 \tan \delta + 5 \times 10^{-4})$
E7-8	$10^{-2} \cdot 10^8$	$1 \times 10^{-4-1}$	1 000	$\pm(0.1 \cdot 0.15)$	$\pm(0.005 \tan \delta + 5 \times 10^{-4})$
P5016	$10^{-2} \cdot 10^8$	$1 \times 10^{-4-1}$	1×10^3	$\pm(0.02 \cdot 0.2)$	$\pm(0.01 \tan \delta + 5 \times 10^{-4})$
			5×10^3		
			1×10^4		
			5×10^4		
“Yantar” meter	0.01-400	$1 \times 10^{-4-1}$	0.01-100	$\pm(0.1 \cdot 2)$	$\pm(5 \cdot 20) \%$

0.03, $\tan \delta = 10^{-4}$, and $TCC \leq 2 \times 10^{-5} \text{ K}^{-1}$. Capacitance boxes have means for connection of such capacitors in parallel to raise the total capacitance to 0.0111 μF .

Mica capacitors, which are smaller in size than air capacitors, often find use as fixed capacitors with $\tan \delta = 5 \times 10^{-4}$ and $TCC = 5 \times 10^{-5} \text{ K}^{-1}$.

Apart from a set of mica capacitors, boxes often contain a variable air capacitor with a calibrated scale to enable a smooth variation of capacitance. Capacitance boxes are available in plug and dial types.

A. C. bridges. The Soviet industry puts out a variety of a.c. bridges for measuring the permittivity and dissipation factor of materials. These instruments are adaptable for the measurement of quantities at various frequencies and voltages. A listing of some of the characteristics of Soviet-made bridges appears in Table 4.2.

4.5. Resonance Methods for Determining C_x and $\tan \delta$

Resonant circuits with lumped parameters (containing inductors, capacitors, and resistors) are designed for the measurement of specimens in the frequency range extending from a few tens of kilohertz to approximately 200 MHz. The physical phenomena that take place in oscillatory circuits are harnessed for the measurement of capacitance and loss tangent. The resonance methods of measurement may be divided into two groups: the first includes tuned circuit methods, and the second generator resonance methods (Fig. 4.10).

Tuned circuit methods use a high-frequency generator whose oscillatory circuit includes a specimen under test; the generator operates at a constant current. Generator resonance methods use either two generators (one being the standard with fixed frequency, and the other the working generator) or one generator whose current varies with the parameters of a test specimen.

Tuned circuit methods. By these methods, C_x and $\tan \delta$ are determined by varying the susceptance or frequency.

Susceptance-variation method. Susceptance is commonly varied by changing the capacitance of a resonant circuit. The circuit diagram includes a high-frequency generator of fixed frequency. The generator is loosely coupled to a measur-

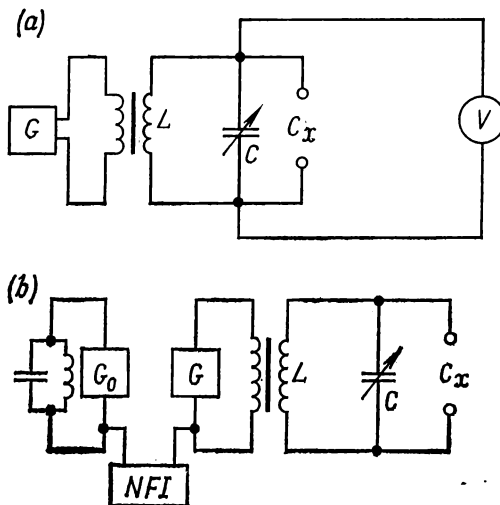


FIG. 4.10. Circuit diagrams for tests with resonance methods
(a) tuned-circuit method; (b) generator resonance method

ing resonant circuit which contains an inductor and variable capacitor (Fig. 4.10a); a test specimen can be connected in parallel with the capacitor. Since the generator produces a constant current, the voltage impressed across the resonant circuit (Fig. 4.11a) passes through a maximum and then falls off with changes in the susceptance (commonly capacitance) of the circuit. The highest voltage implies that the circuit is at resonance. The circuit is not free from losses, for which reason the equivalent circuit contains, along with L and C , a conductance g_c representative of losses (Fig. 4.11b). If we lay off the capacitances (C_0) of a calibration capacitor on the X -axis and realize a function $U(C)$, that is, plot a resonance curve, once with the specimen disconnected and the second time with the specimen placed in the circuit then we can see that the maximum on the second resonance curve

appears to be less acute and shifted to the left. The fact is that in order to adjust the circuit to resonance at the same frequency of oscillations, we have to decrease the capacitance of the capacitor by the value of the specimen capacitance. A decrease in voltage that takes place at a maximum is due to the lossy specimen (C_x) which causes the total conductance to grow by g_x (Fig. 4.11a).

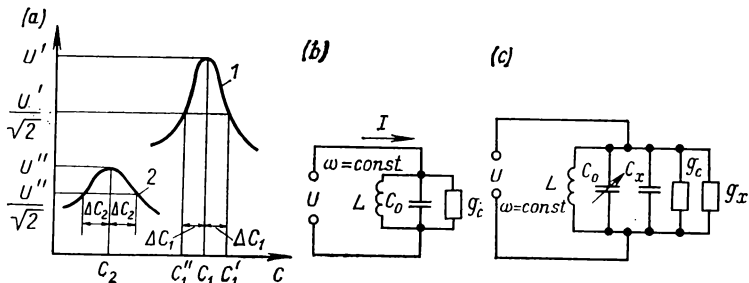


FIG. 4.11. Resonance curves (a) and equivalent circuits with the specimen disconnected (b) and connected (c), illustrating the susceptance-variation method

The circuit is first tuned to resonance with the specimen disconnected to determine the capacitance C_1 of the capacitor (curve 1 on Fig. 4.11a) and the highest voltage U' ; varying the capacitance on both sides of resonance, we find the value ΔC_1 that corresponds to a decrease in voltage to $U'/\sqrt{2}$. This value is chosen with the aim of deriving a simple expression such as Eq. (4.32) for circuit conductance g_c . Connecting now the specimen across the terminals, we adjust again the circuit to resonance and note new values of capacitance C_2 (curve 2 on Fig. 4.11a), and of circuit voltage U'' . At the moment of resonance, the inductive susceptance of the circuit is equal to its capacitive susceptance, so the admittance contains only the real part (conductance). The voltage in the circuit without the specimen, that is, at the first resonance (see Fig. 4.10a), is

$$U' = I \frac{1}{g_c} \quad (4.29)$$

where g_c is the conductance of the circuit with the specimen disconnected; and I is the current in the circuit.

When the circuit is detuned, we obtain a new value of capacitance C'_1 at the voltage $U'/\sqrt{2}$:

$$\frac{U'}{\sqrt{2}} = I \frac{1}{\sqrt{g_c^2 + \left(\frac{1}{\omega L_1} - \omega C'_1\right)^2}} = \frac{I}{y'} \quad (4.30)$$

From the condition of equality of susceptances in the circuit tuned to resonance, we find

$$\omega C_1 = \frac{1}{\omega L_1}, \quad y' = \sqrt{g_c^2 + (\omega C_1 - \omega C'_1)^2} = \sqrt{g_c^2 + (\omega \Delta C_1)^2} \quad (4.31)$$

where $\Delta C_1 = |C_1 - C'_1|$.

Dividing Eq. (4.29) by Eq. (4.30) using Eq. (4.31) and squaring both parts of the equality, we have

$$2 = \frac{g_c^2 + (\omega \Delta C_1)^2}{g_c^2}$$

whence

$$g_c = \omega \Delta C_1 \quad (4.32)$$

The result obtained is of much importance. It appears that we can determine the conductance g_c by decreasing (or increasing) the resonant circuit capacitance relative to its value at resonance by the value ΔC_1 which corresponds to a drop in voltage U' at resonance to $U'/\sqrt{2} = 0.707 U'$. The intercept $2\Delta C_1$ corresponding to $0.707 U'$, where U' is the voltage at resonance, received the name the width of the resonance curve.

From the width of the resonance curve we can find the tuned-circuit quality factor (Q -factor).

For the tuned circuit without the specimen, according to the theory of alternating currents,

$$\frac{1}{Q_1} = \frac{\omega L}{R_c} = \frac{g_c}{\omega C_1} \quad (4.33)$$

Since $g_c = \omega \Delta C_1$, then

$$1/Q_1 = \Delta C_1/C_1 \quad (4.34)$$

where ΔC_1 is a change in capacitance that corresponds to a decrease in voltage U' to $0.707 U'$; and C_1 is the capacitance of the capacitor with the circuit at resonance.

It is also convenient to express the specimen parameters C_x and $\tan \delta$ through the Q -factor of the circuit. With the specimen (C_x) disconnected, the circuit is tuned to resonance and then the Q_1 -factor is measured and the capacitance C_1 noted. Knowing these parameters, we can find g_c from formula (4.33). The Q_1 -factor may be determined from the width of the resonance curve:

$$g_c = \omega C_1 / Q_1 \quad (4.35)$$

Inserting the capacitance C_x into the circuit and varying the capacitance, we retune the circuit, note the capacitance C_2 of the variable capacitor and measure the Q -factor, Q_2 . Since the frequency is invariable, the capacitance $C_2 + C_x$ in the retuned circuit must be equal to C_1 . Hence

$$C_x = C_1 - C_2 \quad (4.36)$$

The total conductance

$$g_c + g_x = \frac{\omega (C_2 + C_x)}{Q_2} = \frac{\omega C_1}{Q_2} \quad (4.37)$$

Using Eq. (4.35) for the conductance g_c , we have

$$g_x = \omega C_1 \left(\frac{1}{Q_2} - \frac{1}{Q_1} \right) \quad (4.38)$$

The sought-for dissipation factor is

$$\tan \delta = \frac{g_x}{\omega C_x} = \frac{C_1}{C_x} \left(\frac{1}{Q_2} - \frac{1}{Q_1} \right) \quad (4.39)$$

The reverse order of measurement is also possible: the first tuning is secured with the specimen (C_x) inserted in the circuit, and the second tuning with the specimen removed.

Frequency-variation method. This is a variety of the tuned circuit method for determining C_x and $\tan \delta$ by changing the frequency. The method demands a high-frequency generator and a precision frequency meter or wavemeter. A source G with a wavemeter W is connected across a resonant circuit (Fig. 4.12a) containing an inductor L and capacitor C of fixed capacitance. By changing the frequency of the generator, we tune the circuit to resonance representative of the highest reading of the vacuum-tube voltmeter V . Let the frequency setting (at resonance), with the specimen removed (Fig. 4.12c), be ω_1 and the voltage noted be U_1 . Detune the

circuit by setting the frequency to ω'_1 to reduce the voltmeter reading to $U_1/\sqrt{2}$ ($0.707 U_1$); a change in the angular frequency (the width of the resonance curve) is

$$\Omega_1 = \omega'_1 - \omega_1 \quad (4.40)$$

Find the Q -factor and conductance g_c of the circuit (curve 1

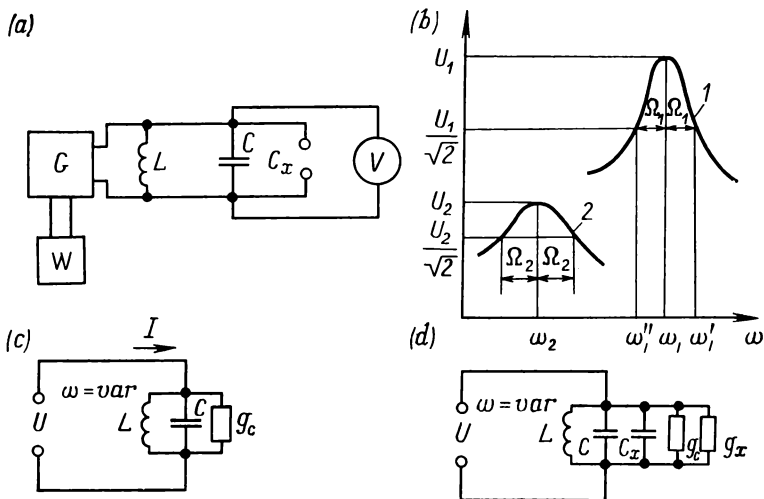


Fig. 4.12. Circuit diagram (a), resonance curve (b), and equivalent circuits with the specimen disconnected (c) and connected (d), illustrating the frequency-variation method

on Fig. 4.12b). At resonance

$$U_1 = I \frac{1}{g_c} \quad (4.41)$$

With the circuit detuned

$$\frac{U_1}{\sqrt{2}} = I \frac{1}{\sqrt{g_c^2 + \left(\frac{1}{\omega'_1 L} - \omega'_1 C \right)^2}} \quad (4.42)$$

Transform the expression in brackets, considering that $\omega'_1 = \omega_1 + \Omega_1$ and that at resonance $\omega_1 L = 1/\omega_1 C$,

$$\frac{1}{\omega'_1 L} - \omega'_1 C = C \frac{\omega_1^2 - (\omega_1 + \Omega_1)^2}{\omega'_1} = C \frac{-2\Omega_1 \omega_1 - \Omega_1^2}{\omega'_1}$$

Since the amount of detuning is generally small, we may omit Ω_1^2 for its value is negligible in comparison with $2\Omega_1\omega_1$. Also, observing the same conditions, we may assume that $2\Omega_1\omega_1 = 2\Omega_1\omega_1'$. Whence

$$\frac{1}{\omega_1' L} - \omega_1' C = -2C\Omega_1 \quad (4.43)$$

Substituting this expression in Eq. (4.42) gives

$$\frac{U_1}{\sqrt{2}} = I \frac{1}{\sqrt{g_c^2 + (2\Omega_1 C)^2}} \quad (4.44)$$

Dividing Eq. (4.41) by Eq. (4.44) and performing transformations (on condition that I is constant), we obtain the expressions for g_c and Q_1 :

$$g_c = 2\Omega_1 C_1, \quad \frac{1}{Q_1} = \frac{g_c}{\omega_1 C} = \frac{2\Omega_1}{\omega_1} \quad (4.45)$$

Because

$$\Omega_1 = 2\pi\Delta f_1, \quad \omega_1 = 2\pi f_1, \quad \text{then} \\ g_c = 4\pi\Delta f_1 C, \quad 1/Q_1 = 2\Delta f_1/f_1 \quad (4.46)$$

The quantity $2\Omega_1$ is called the bandwidth of the circuit. So, the quantity which is the reverse of the Q -factor of the circuit is equal to the bandwidth divided by the resonant frequency.

With the specimen connected (Fig. 4.12d), it is again possible to tune the circuit to resonance by changing the frequency to ω_2 , the resonant voltage now being U_2 (curve 2 on Fig. 4.12b). By detuning the circuit to reduce U_2 to $0.707 U_2$, it is possible to determine the bandwidth, $2\Omega_2$ and, in analogy with Eq. (4.45), write the expression for $1/Q_2$:

$$\frac{1}{Q_2} = \frac{g_c + g_x}{\omega_2 (C + C_x)} = \frac{2\Omega_2}{\omega_2} \quad (4.47)$$

For determining the specimen capacitance, we have two conditions of resonance:

for the circuit with the specimen removed

$$\omega_1^2 = \frac{1}{LC} \quad (4.48)$$

for the circuit with the specimen connected

$$\omega_2^2 = \frac{1}{L(C + C_x)} \quad (4.49)$$

Cancelling L from these expressions gives

$$C_x = C [(\omega_1/\omega_2)^2 - 1] = C [(f_1/f_2)^2 - 1] \quad (4.50)$$

To determine $\tan \delta$, we can use formula (4.39) and substitute into it the derived expression for C_x :

$$\tan \delta = \frac{C}{C_x} \left(\frac{1}{Q_2} - \frac{1}{Q_1} \right) = \frac{Q_1 - Q_2}{Q_1 Q_2 [(f_1/f_2)^2 - 1]} \quad (4.51)$$

It is sometimes more convenient to vary the frequency in another manner. Let the resonant frequency be f_0 ; now decrease f_0 to f'_0 (or increase to f''_0) in order to reduce the voltage U_0 , or, which is the same, the Q -factor, by one-half.

The current at resonance

$$I = U_0 g_c \quad (4.52)$$

With the circuit detuned and the current kept constant, we have

$$I = \frac{U_0}{\sqrt{2}} \sqrt{g_c^2 + \left(\frac{1}{\omega'_0 L} - \omega'_0 C \right)^2} \quad (4.53)$$

Transform the radicand in the brackets, considering that

$$f'_0 = f_0 + \Delta f, \quad f_0^2 = \frac{1}{4\pi^2 LC}$$

Hence

$$\begin{aligned} \frac{1}{2\pi L (f_0 + \Delta f)} - 2\pi C (f_0 + \Delta f) &= 2\pi C \left[\frac{f_0^2}{f_0 + \Delta f} - (f_0 + \Delta f) \right] \\ &= \frac{2\pi C (-2f_0 \Delta f) \left(1 + \frac{\Delta f}{2f_0} \right)}{f_0 (1 + \Delta f/f_0)} \approx -4\pi C \Delta f \end{aligned}$$

because $\Delta f/(2f_0) < \Delta f/f_0 \ll 1$ at a small amount of detuning.

Equating the right sides of Eqs. (4.52) and (4.53) gives

$$2g_c = \sqrt{g_c^2 + 4\pi^2 C^2 4 (\Delta f)^2}$$

Since $2\Delta f = f''_0 - f'_0$, then

$$g_c = \frac{1}{\sqrt{3}} 2\pi C (f''_0 - f'_0) \quad (4.54)$$

where f'_0 and f''_0 are frequencies corresponding to $U_0/2$. Thus the Q -factor expressed in terms of the amount of off-resonance at a certain frequency setting is

$$Q_0 = \frac{2\pi f_0 C}{g_c} = \frac{\sqrt{3} f_0}{f''_0 - f'_0} \quad (4.55)$$

Detuning of the bridge by changing the frequency (or capacitance) to reduce the voltmeter reading to $U_0/2$ is applicable in the precision measurement of the Q -factor, for example, in type E9-4 devices.

The main advantage of the susceptance-variation method lies in the fact that the frequency does not enter into the calculation formulas and, thus, there is no need for its measurement or control. By thoroughly elaborating the circuit and using high-frequency standard elements, it is possible to perform measurements within the specified limits of error. The resonance methods of frequency and susceptance variations find use in Q -meters. It should be noted that the resonance methods can secure an insignificant error in the measurement of C_x only if $\tan \delta$ is relatively small. A large loss tangent entails an added variation in frequency. The effect of $\tan \delta$ of a test specimen on frequency is expressed by the relation

$$\omega = \omega_0 \sqrt{\frac{1 + \tan^2 \delta}{1 + 1/Q_L^2}} \quad (4.56)$$

where $\omega_0 = 1/LC$ is the resonant frequency of the circuit containing a capacitor C and a loss-free inductor L , both being loss-free; and Q_L is the Q -factor of the inductor at resonance. Some instruments offset the influence of $\tan \delta$ on frequency with the aid of an adjustable resistor placed in the resonant circuit.

Generator resonance methods. These are in turn subdivided into capacitance measurement methods and loss tangent measurement methods.

Capacitance measurement methods use a standard-signal generator G_0 and a null-frequency indicator NFI which controls the frequency of the resonant circuit fed from its own generator G (see Fig. 4.10b). First the circuit, with the test specimen (C_x) disconnected, is tuned to resonance to the frequency of the standard generator G_0 with the aid of the indicator NFI to note the capacitance C_1 ; then the circuit with the specimen connected is again adjusted to resonance to the same frequency setting to read a new value, C_2 , on the variable capacitor. The capacitance C_x is found from the formula

$$C_x = C_1 - C_2$$

Loss tangent measurement methods use a constant-frequency variable-current generator; the methods basically rely on variations in the feed current (the d.c. component of the plate current) of a generator vacuum tube with changes in the conductance of the resonant circuit. An increase in the conductance after connecting a lossy specimen (C_x) in the circuit entails a decrease in the amplitude of high-frequency oscillations. This in turn leads to a drop in the negative grid bias and rise in the feed current I_p in the vacuum tube. A change in the feed current is equivalent to a change in the plate resistance R_p , that is, the internal resistance between the plate and cathode in the vacuum tube. The resistance R_p serves as one of the arms of a d.c. bridge (Fig. 4.13). It is possible to balance this bridge without the test specimen (C_x). On connecting the lossy specimen in the circuit, the conductance of the circuit grows, which results in the increased feed current and decreased resistance R_p ; this upsets the balance of the bridge and results in the appearance of current in the branch connecting the opposite junctions of the bridge. To keep the frequency of oscillations invariable before connecting the specimen into the circuit, the capacitance of the variable capacitor is reduced by a value of C_x . Knowing the current in the branch between the opposite junctions of the unbalanced bridge, we can determine $\tan \delta$. This method permits constructing measuring devices which can read $\tan \delta$ directly.

The resonance method of measurement underlies the principle of the "Tangens-2M" measuring device that indicates directly the permittivity ϵ and $\tan \delta$. The block diagram of the meter is shown in Fig. 4.14. The measuring cell C_0 is part of a parallel circuit $C2-L$. A signal generator G supplies to this circuit high-frequency voltage modulated in frequency with a mechanical modulator M (motor). With the switches turned to the left, the cell C_0 is connected to the measuring circuit and the auxiliary variable capacitor $C1$ to the master circuit of a standard generator G_0 . The frequency modulated output of a detector D is fed to a phase-sensitive amplifier $A1$ which controls a motor $M1$ of capacitor $C2$. This capacitor makes the circuit responsive to a frequency ω of the generator G . The automatic control unit then connects the capacitor $C1$ into the circuit in place of the cell and also

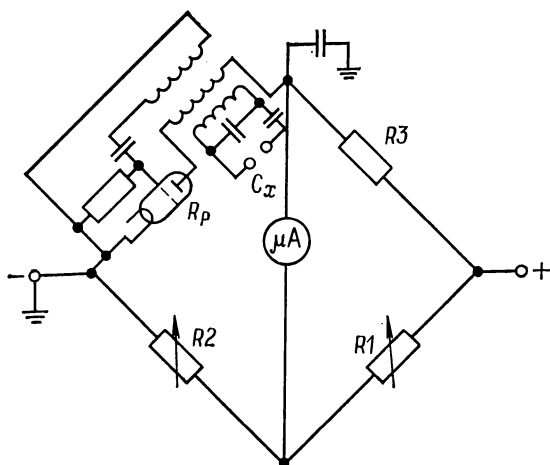


FIG. 4.13. Circuit diagram for measurement of $\tan \delta$ by the generator resonance method

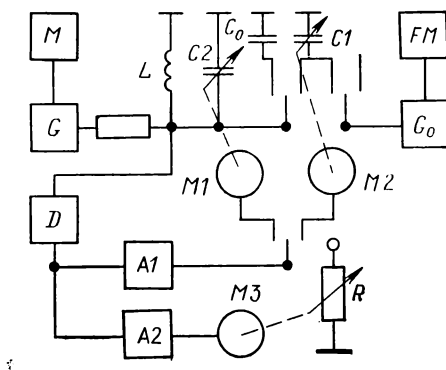


Fig. 4.14. Block diagram of a device for measuring permittivity and loss tangent

a motor $M2$ into the output circuit of the amplifier $A1$. The capacitance of the capacitor $C1$ automatically replaces the cell capacitance in the circuit, that is, its capacitance becomes equal to the cell capacitance. As the cell is again

switched into the circuit, the capacitor becomes connected to the standard generator G_0 whose frequency is measured by a frequency meter FM . A change in frequency is used to determine permittivity. The loss tangent is found from the relative changes in voltage across the measuring circuit, $\Delta U_x/U_0$, where U_0 is the amplitude of voltage with the cell being empty; and ΔU_x is a change in voltage after filling the cell with a test substance. The voltage across the circuit is measured automatically by the compensation method using a phase-sensitive amplifier $A2$, motor $M3$, and variable resistor R .

The technical data on some resonance instruments are given in Table 4.3.

TABLE 4.3

Resonance Instruments

Type	Measuring range for C , ϵ , and $\tan \delta$	Measurement error, %	Frequency range, Hz
E4-7 (E9-7)	$C=25$ to 459 pF	1-2	$5 \times 10^3=35 \times 10^6$
E4-5A (E9-5A)	$C=10$ to 100 pF	—	$(15 \text{ to } 250) \times 10^6$
E4-10	$C=80$ to $110\,000$ pF	1-2	$(1 \text{ to } 100) \times 10^3$
“Tangens-2M”	$\epsilon=1$ to 100	0.02-2	10^5 to 10^7
meter	$\tan \delta=0.3 \times 10^{-4}$ to 1	5-20	

4.6. Noncontact Methods of Measuring ϵ and $\tan \delta$

Tests on solid dielectrics usually require deposited electrodes on the surface of specimens, which involves time and labor. The results of measurement often depend on the material of an electrode and the method of its deposition, which is especially the case with film electrodes. In a number of cases inclusions present between the electrode and dielectric or interlayers of petrolatum and oil become a source of substantial error.

The use of specimens with electrodes necessitates introducing corrections for the edge capacitance and the electrode and terminal capacitance.

Recent years have seen the introduction into practice of noncontact methods for determining ϵ and $\tan \delta$ of solid insulating materials.

A method of one medium. This method employs a two-electrode measuring cell filled with a liquid dielectric whose ϵ_1 and $\tan \delta_1$ are known to a high precision. In the measuring procedure it is first necessary to measure the capacitance C_1 of the cell filled with a standard liquid, then immerse into it a flat test specimen between the electrodes and note a capacitance C_2 and $\tan \delta_2$. The capacitances C_1 and C_2 are usually expressed in picofarads.

If ϵ_x of the specimen differs from ϵ_1 of the liquid by about $\pm 5\%$, the permittivity may be found by the formula

$$\epsilon_x = \epsilon_1 + \frac{(C_2 - C_1) d \epsilon_1}{s C_1}$$

Here d is the interelectrode distance, mm, and s is the specimen thickness, mm.

If the difference between ϵ_x and ϵ_1 is in excess of $\pm 5\%$, a more precise expression proves useful:

$$\epsilon_x = \epsilon_1 + \frac{C_2 - C_1}{\frac{C_1}{\epsilon_1} \frac{s}{d} - \frac{(C_2 - C_1)(1 - s/d)}{\epsilon_1}}$$

The loss tangent of the material under test may be calculated by the formula

$$\tan \delta = \tan \delta_2 \left[1 + \frac{\epsilon_x (d - s)}{\epsilon_1 s} \right] - \tan \delta_1 \frac{\epsilon_x}{\epsilon_1} \frac{d - s}{s}$$

The choice of a liquid medium is of much importance since one must know for certain the values of ϵ_1 and $\tan \delta_1$. As the permittivity ϵ_1 of nonpolar liquids decreases with increased temperature it is necessary to introduce into the calculation formulas the values of ϵ_1 , which correspond to the temperature at the moment of measurement, using the temperature dependence of ϵ (Fig. 4.15). The condition $\epsilon_1 \approx \epsilon_x$ should also be observed. Thus for the reasons stated above, in tests on polyethylene ($\epsilon_x = 2.3$), chromatographic anhydrous benzene ($\epsilon_1 = 2.28$) makes a suitable medium; for foam plastics ($\epsilon_x = 1.1$ to 1.3), this is the air ($\epsilon_1 = 1$); and for polytetrafluoroethylene, either cyclohexane or capacitor oil.

Since benzene is toxic, the measurements are made with the cell kept in an exhaust chamber. Toxic liquids should be handled with much care in accordance with pertinent

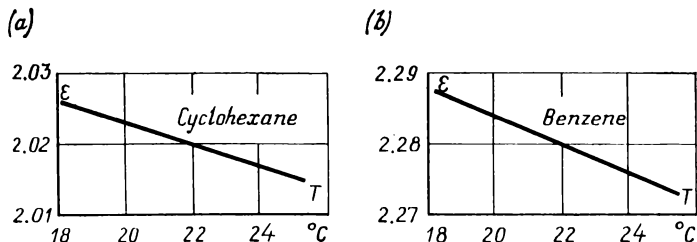


FIG. 4.15. Permittivity of cyclohexane (a) and benzene (b) as a function of temperature

instructions. Also, precautions should be taken and safety rules observed because benzene and cyclohexane are readily inflammable substances. Besides, reference liquids are hygroscopic, therefore they should be held in vessels closed with ground stoppers and be subjected to prolonged drying after use.

Before filling it with a liquid, the measuring cell is thoroughly cleansed, dried, and rinsed twice with the standard liquid. To eliminate the effect of bubbles between the electrode and specimen, the capacitance measurements on the cell are started 1 min after immersing the specimen into the liquid. The interelectrode spacing should be such that a specimen can freely enter into the gap. Thus with $d = 1.8$ mm, the thickness s of a specimen should be 1.5 mm and its diameter 5 cm. In use are also rectangular specimens. The measurements are commonly done over the frequency range from 1 to 100 kHz, though this method is adaptable for use at lower frequencies (up to 50 Hz) and higher frequencies (up to 10 MHz).

A drawback of this method is that it is sometimes difficult to choose standard liquids which would cover a wide range of permittivities characteristic for a great many of the modern materials. As the difference between ϵ_1 and ϵ_x grows high, the geometrical dimensions of the specimen and cell begin to tell on the accuracy of measurement.

A method of two media. The use of two media obviates to a large extent the above difficulty. Air can serve as the first medium and a silicone liquid, for example, as the second medium. Keeping the distance between the electrodes of a measuring cell constant, we first measure the empty cell filled with air to determine C_1 , then measure C_3 with the specimen in place. Next we find C_2 and $\tan \delta_2$ for the cell filled with a silicone liquid with the specimen removed, and then C_4 and $\tan \delta_4$ with the specimen in place. Let us introduce the following designations:

$$\Delta C_1 = C_3 - C_1, \quad \Delta C_2 = C_4 - C_2$$

For the mentioned media (air and liquid),

$$\varepsilon_x = \varepsilon_a + \frac{\varepsilon_a}{C_1} \frac{\Delta C_1 C_4 (C_2 - C_1)}{\Delta C_1 C_4 - \Delta C_2 C_3}$$

where $\varepsilon_a = 1.00058$ is the permittivity of air. Further,

$$\tan \delta = \tan \delta_4 + \frac{\left(\varepsilon_x \frac{C_1}{\varepsilon_a} - C_4 \right) (\tan \delta_4 - \tan \delta_2)}{\Delta C_2}$$

In using a silicone liquid (and other liquids too) it proves essential to wash out thoroughly contaminants from the cell before starting with the tests and exclude the formation of bubbles in the space between the specimen and electrodes. It is easy to see that this method obviates the need for determining the specimen thickness, interelectrode gap, and permittivities of standard media, though the measuring procedure turns out to be more complex.

Along with the advantages, the noncontact measurement methods have some limitations. Tests in the air can only be made at low voltages, until the corona (partial discharge) builds up in the narrow airgap between the specimen and electrodes. The corona discharge can bring about substantial errors in the measurement of ε_x and $\tan \delta$. Apart from the condition $\varepsilon_1 \approx \varepsilon_x$, which must be met when employing the method of one medium, the requirements that the media should be inert to the material under test (not cause it to swell, dissolve, etc.) set limits on the choice of these standard liquids.

4.7. Calculation of ε and $\tan \delta$

The result obtained in measuring the capacitance with a bridge or some other device is the sum of capacitances which include the specimen capacitance C_x , edge capacitance C_e , and ground capacitance C_z (capacitance with respect to ground). The last two capacitances should be excluded from the measurement result, but then it is necessary to determine them.

The edge capacitance is a function of the design, shape, and size of the electrodes and the cell. We have shown earlier that the capacitance measurement methods can use either a two-electrode or three-electrode system; the dimensions of electrodes in the latter system may be identical or different and can or cannot coincide with the dimensions of a specimen. Where a specimen and electrodes have the same diameters (see Fig. 4.1a), the electric field in the specimen is practically uniform because the whole scattering field is in the air. If the electrodes have a substantially smaller thickness than the specimen, the edge capacitance C_e becomes $C_e = \pi d (0.029 - 0.058 \log t)$

If the thickness of electrodes is comparable to the specimen thickness

$$C_e = \pi d \left(0.0326 \log \frac{d}{t} + z + 0.0031 \right)$$

where

$$z = 0.0326 \left[\left(1 + \frac{a}{t} \right) \log \left(1 + \frac{a}{t} \right) - \frac{a}{t} \log \frac{a}{t} \right]$$

If the electrodes are smaller in size than the specimen (see Fig. 4.1b, c), one should carefully center the electrodes since eccentricity heavily changes the edge capacitance. At $a \ll t$ and with the same diameters of electrodes (see Fig. 4.1b)

$$C_e = \pi d (0.019\varepsilon_g - 0.058 \log t + 0.010)$$

If electrodes differ in diameters (see Fig. 4.1c)

$$C_e = \pi d (0.041\varepsilon_g - 0.077 \log t + 0.045)$$

where ε_g is an approximate value of the specimen permittivity.

For specimens of the tubular shape (see Fig. 4.1*d*), the thickness t must be smaller than $0.1 D_1$. In this case

$$C_e = \pi (D_1 + t) (0.019 \epsilon_R - 0.058 \log t + 0.010)$$

The correction factor B (sec. Sec. 3.4) allows for field distortion near the edges of electrodes in a three-electrode system. The ground capacitance of a high electrode is given in manuals on a measuring set. It is estimated experimentally or from calculations.

The permittivity of a dielectric material is found as the ratio of the capacitance C_x of a capacitor with the test dielectric between the electrodes to the capacitance C_0 of a capacitor with the same arrangement of electrodes but having a vacuum (air) for its dielectric:

$$\epsilon = C_x / C_0$$

The capacitance C_0 for flat specimens in a two-electrode system (see Fig. 4.1*a*, *b*, *c*) is

$$C_0 = 0.0695 \frac{d^2}{t}$$

and for tubular specimens (Fig. 4.1*d*)

$$C_0 = \frac{0.2416l}{\log D_2 - \log D_1}$$

With a three-electrode system used, the measured $\tan \delta$ is just the sought-for value; in a two-electrode system, the actual value of $\tan \delta$ is computed by the formula

$$\tan \delta = \frac{C'_x}{C_x} \tan \delta'$$

where $\tan \delta'$ is the measured value.

Micrometer-electrode systems allow for the calculation of ϵ directly from the results of observation. As described earlier, the specimen is clamped in the micrometer electrodes with a micrometer screw. The readings on the micrometer dial are then taken to note the distance t' between the electrodes, that is, the specimen thickness. Next C'_x is measured. The specimen is then removed from the cell and the distance between the electrodes is adjusted with the micrometer screw to have the capacitance of the empty cell equal to the capacitance of the cell with the specimen clamped between the micrometer electrodes. A new reading t'' of the micrometer

is taken. The permittivity is equal to the ratio between the two readings

$$\varepsilon = t'/t''$$

The calculation of loss tangent is somewhat more complex. The procedure of measurement and the choice of calculation formulas depend on the measuring devices employed. If a measuring unit or device indicates the loss tangent directly, then, as with the measurement of ε , the value of $\tan \delta$ is found from the two readings by the formula

$$\tan \delta = \frac{C_1}{C_x} (\tan \delta_1 - \tan \delta_2)$$

where $\tan \delta_1$ is the loss tangent of the cell with the specimen in place, $\tan \delta_2$ is the loss tangent of the cell with the specimen removed, C_1 is the total capacitance of the cell with the specimen connected, and C_x is the specimen capacitance estimated by the formula

$$C_x = 0.0695 d^2/t''$$

where d is the electrode diameter.

In making measurements by a resonance method, in which case the instrument will read the Q -factor, the loss tangent may be calculated with the formula

$$\tan \delta = \frac{Q_2 - Q_1}{Q_1 Q_2} \frac{C_{res}}{C_x}$$

where Q_1 and Q_2 are the factors of quality for the circuit with and without the specimen respectively, C_{res} is the capacitance of the resonant circuit with the specimen disconnected, and C_x is the test specimen capacitance.

TABLE 4.4

Formulas for Calculation of ε and $\tan \delta$ of Liquid Materials

Cell type	Permittivity	Loss tangent
Three-electrode	$\varepsilon = \frac{C_1}{C_2}$	$\tan \delta = \tan \delta_1 - \frac{C_0}{C_1} \tan \delta_0$
Two-electrode	$\varepsilon = \frac{C_1 - C_{str}}{C_0 - C_{str}}$	$\tan \delta = \frac{C_1}{C_1 - C_{str}} \left(\tan \delta_1 - \frac{C_0}{C_1} \tan \delta_0 \right)$

The calculation of ε and $\tan \delta$ of liquid materials is similar to the calculation made for low frequencies (see Sec. 3.4). The calculation formulas for a two-electrode and a three-electrode cell are given in Table 4.4.

The percentage error in permittivity and loss tangent shall be within 4% and 7% respectively.

From the results of individual observations we can find the estimate of standard error, S , by the formula

$$S = \sqrt{\frac{\sum \Delta_i^2}{n-1}}$$

where $\Delta_i = \varepsilon_i - \bar{\varepsilon}$ or $\Delta_i = \tan \delta_i - \overline{\tan \delta}$, and n is the number of observations.

4.8. Measurement of TCC

The permittivity of a material does not remain constant with temperature changes. Depending on the type of material and the temperature range, the permittivity can grow or fall with increasing temperature. A factor used to estimate changes in the permittivity of a material with changes in its temperature is known as the mean temperature coefficient of permittivity, $\text{TC}\varepsilon$, whose expression takes the form

$$\text{TC}\varepsilon = \frac{\varepsilon_2 - \varepsilon_1}{\varepsilon_1 (T_2 - T_1)}$$

where ε_1 and ε_2 are the permittivities of the specimen at T_1 and T_2 respectively. The unit of $\text{TC}\varepsilon$ is the kelvin with a negative exponent equal to one (K^{-1}).

Since the permittivity of a specimen is proportional to its capacitance, it is possible to relate $\text{TC}\varepsilon$ to the mean TC of capacitance TCC. The formula for the latter is

$$\text{TCC} = \frac{C_2 - C_1}{C_1 (T_2 - T_1)}$$

where C_1 and C_2 are capacitances of the specimen at T_1 and T_2 respectively. The relation between TCC and $\text{TC}\varepsilon$ has the form

$$\text{TCC} = \text{TC}\varepsilon + \alpha$$

where α is the temperature coefficient of length. Neglecting changes in the linear dimensions of a specimen with tempera-

ture changes, the $\text{TC}\epsilon$ and TCC of the specimen may be assumed equal in magnitude.

It is thus possible to replace the measurements of $\text{TC}\epsilon$ by the measurements of TCC . The instruments designed for such measurements must be sensitive to very small changes

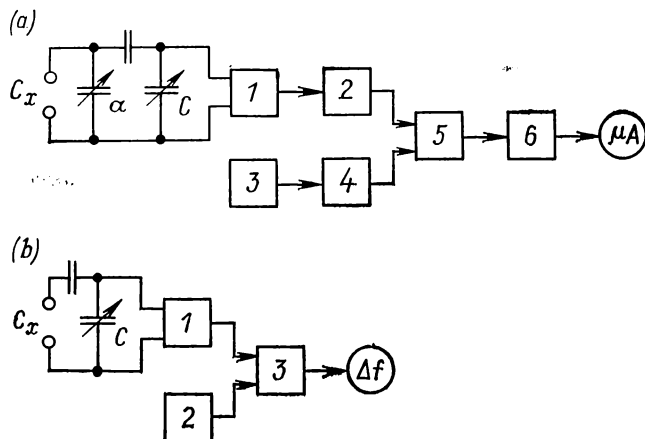


FIG. 4.16. Block diagrams of devices for determining TCC
(a) method of beats; (b) frequency-variation measurement method

in capacitance, $\Delta C = C_2 - C_1$, which occur as a result of temperature changes, $\Delta T = T_2 - T_1$. The difference ΔC can be as small as fractions of a picofarad. Obviously, a measuring set must include a unit capable of varying and keeping the temperature T at the desired level with a definite accuracy. The measuring accuracy also depends on the frequency stability during measurements.

Instruments operating on the principle of beats have found most extensive uses in the measurement of TCC (Fig. 4.16). A test specimen with terminals is connected in the resonant circuit of an oscillator 1. The frequency produced in this case will depend on the specimen capacitance C_x . The instrument has a reference oscillator 3 with the frequency stabilized by a quartz crystal and kept invariable. Both oscillators send signals to amplifiers 2 and 4 where they are amplified and passed to a mixer 5 and an amplifier-detector 6 which give

a difference frequency (beat frequency). First the circuit of the oscillator 1, with the specimen in place and heated to a temperature T_1 , is adjusted to resonate at the frequency of the reference oscillator 3, using for the purpose a capacitor C . A microammeter μA gives a zero-beat indication as the two frequencies become equal in magnitude. Heating the specimen to a temperature T_2 changes its capacitance and entails a change in the frequency of the oscillator 1. By adjusting a variable capacitor α , the oscillator 1 is again tuned to resonate at the frequency of the oscillator 3. It is obvious that a change in the capacitance of the tuning capacitor between the first and the second setting is equal to a change in the capacitance of the specimen. Knowing the change in capacitance and the corresponding change in temperature, it is easy to calculate the TCC of the specimen.

The described principle of measurement underlies the operation of measuring units and sets of the types TRE-1-2M, TRE-2-2M, TRE-3M, C1, and others. The type TRE-2-2M measuring set consists of three components: a heating chamber, a temperature control unit, and an instrument. The chamber is furnished with heating elements and a fan. To exclude the effect of ambient temperature on the results of measurement, the set is installed away from windows, doors, and heating arrangements. This set can measure TCC from 3×10^{-5} to $1 \times 10^{-3} \text{ K}^{-1}$. The capacitance measuring range is from 100 to 1 000 pF. The error in measuring capacitance is $\pm 1\%$, and that in measuring TCC within $\pm (0.05 \text{ TCC} + 5 \times 10^{-6}) \text{ K}^{-1}$. Measurements are performed at a specimen temperature of 30 to 70°C. The type TRE-3M set is designed to carry out measurements on large specimens whose capacitance lies within 5 to 30 pF.

The development of frequency-variation and frequency-digital measurement methods had led to a modification of the described method and to a simplified measuring procedure. Measuring devices here detect a change in frequency rather than in capacitance. The block diagram of one such device is illustrated in Fig. 4.16b. A capacitor C is adjusted only once at the temperature T_1 to have the frequency of a test oscillator 1 equal to that of a reference oscillator 2. At the temperature T_2 the oscillator 1 will generate voltage at

a different frequency. This frequency difference Δf is discriminated by a mixer 3 and indicated by an instrument. The device may have no reference oscillator 2. In this case the frequency f_1 corresponding to the temperature T_1 can be stored in an appropriate memory element and then retrieved and subtracted from f_2 by a frequency discriminator, a reversible counter, or some other frequency meter. Since the frequency difference Δf is a function of TCC, the scale of an instrument can be calibrated to read the values of TCC directly. There is no need here to measure the specimen capacitance C_x .

The frequency-variation method has found application in the measuring sets of the types TKE-6, TKE-7, and C2. The TKE-7 excels the others in accuracy. It can measure TCC in the range from -800×10^{-6} to $+800 \times 10^{-6} \text{ K}^{-1}$ with an error kept within $\pm(0.03 \text{ TCC} + 2 \times 10^{-6}) \text{ K}^{-1}$. The capacitance measuring range is from 60 to 200 pF. Measurements are taken at a specimen temperature of 40, 80, and 120°C . The TKE-6 serves to make tests on small specimens with a capacitance from 1 to 30 pF. This set can measure TCC at the same temperature as the TKE-7 but its error of measurement is somewhat higher, $\pm(0.05 \text{ TCC} + 2 \times 10^{-6}) \text{ K}^{-1}$.

The common limitation of the described methods rests on the difference in frequency between the currents flowing through the specimen on heating it to temperatures T_1 and T_2 . This results in an additional frequency error that reaches $\pm(2 \text{ to } 5) \times 10^{-6} \text{ K}^{-1}$. Bridge-circuit measurement methods can eliminate frequency error. The use of these methods for the measurement of a capacitance C and its variation ΔC has become possible only in the last years owing to the creation of high-sensitive a.c. bridges. Bridge circuits can measure ΔC to a higher accuracy because stray parameters here affect the condition of balance to a lesser degree than is the case with frequency-variation methods.

In the bridge methods of measurement, the capacitance of a specimen held in a temperature-controlled chamber is measured with the bridge circuit first at the temperature T_1 and then at T_2 to obtain the values C_1 and C_2 and thus calculate TCC in the interval T_1 - T_2 . Some bridges can read directly $\Delta C = C_1 - C_2$.

Sets of the types TKE-10A and 6025 operate on the bridge

principle. The TRE-10A consists of a thermocryostat and measuring unit. The temperature in the chamber of the thermocryostat can be adjusted over the range from -125 to $+140^{\circ}\text{C}$. The temperature change ΔT for a specimen is 40°C . It is possible to place in the chamber up to 15 specimens at a time and then connect each in turn into the measuring circuit. The measuring unit is an inductance-capacitance bridge with a self-balancing branch, inductively coupled arms, and inductive voltage dividers. The set can measure the TCC of specimens at a frequency of 300 kHz over the TCC range from $-4\,000 \times 10^{-6}$ to $+4\,100 \times 10^{-6} \text{ K}^{-1}$. The measurement error does not exceed $\pm (0.05 \text{ TCC} + 2 \times 10^{-6}) \text{ K}^{-1}$ at a specimen capacitance varying from 1 to 10 000 pF. The procedure of measuring the TCC of specimens is as follows. The temperature in the chamber is set at T_1 , then the capacitance C_1 of every specimen is measured in succession and the instrument reading for each noted. The specimens are now heated to temperature T_2 and the previously measured capacitance C_1 is set for each specimen. Next the capacitive balance is secured at the given temperature to obtain the values of $\Delta C/C_1$ and TCC for each specimen.

BREAKDOWN STRENGTH

•

5.1. General

The working voltage applied to an electrical insulating material must be much lower than the voltage which causes the material rupture. Electrical breakdown results from an electrical discharge through a material at a minimum voltage, called breakdown, or disruptive, voltage U_{br} . In some cases voltages far lower than the breakdown voltage give rise to a surface discharge that does not penetrate deep into the bulk of a material. This is a surface, or creeping, breakdown occurring at a surface breakdown voltage.

The basic characteristic of an electrical insulating material is its breakdown, or dielectric, strength E_{br} (also called electric strength) which is a minimum strength of the uniform electric field that causes dielectric breakdown. The calculation of breakdown strength calls for measuring the breakdown voltage of the material under test. If we express U_{br} in volts and the thickness of a dielectric at the point of breakdown in meters, the breakdown strength E_{br} will be in volts per meter (V/m).

The breakdown voltage U_{br} is proportional to the electric field strength only if the field is uniform. Such a field exists between two electrodes which have the shape of the bodies of revolution; the surface of these electrodes may be described by Rogovsky equations.

In practice, it is common to use electrodes of a simple shape, in the form of discs with rounded edges or as spheres; the field produced between such electrodes is very nearly uniform under certain conditions. In a uniform field

$$E_{br} = U_{br}/t \tag{5.1}$$

where t is the thickness of a material.

In testing sheet materials with flat electrodes, a uniform field builds up only in the medium part of the specimen clamped between the electrodes (Fig. 5.1a), while at the electrode edges the field is subject to distortion. To guard

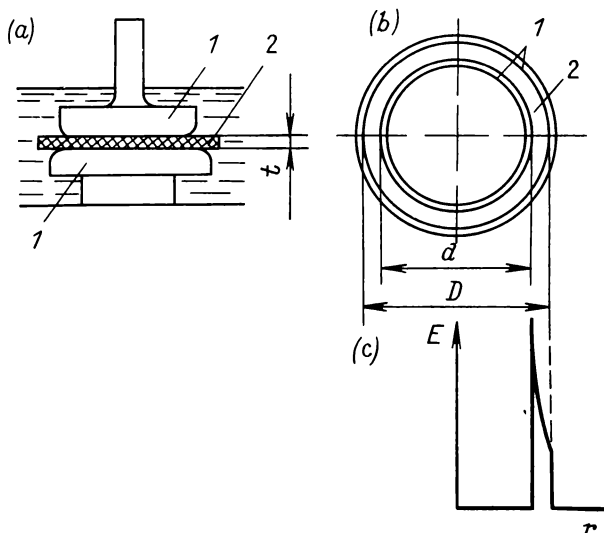


FIG. 5.1. Flat solid specimen (a), tubular solid specimen (b), and field strength-radius relation (c)

against an edge or surface breakdown, a specimen 2 with electrodes 1 is immersed into transformer oil or any other liquid of high dielectric strength.

In a tubular specimen (Fig. 5.1b) the field strength varies along the radius; the field is the strongest at points lying close to the inner electrode, where the radius is equal to $d/2$. The breakdown strength is determined from the highest value of field strength. The value of E_{br} is calculated by the formula

$$E_{br} = \frac{2U_{br}}{d \ln \frac{D}{d}} \quad (5.2)$$

where d and D are the inside and the outside diameter of the specimen.

With electrodes having a spherical surface, the field appears to be a little nonuniform. In a nonuniform field the breakdown voltage U_{br} is always lower than in a uniform field, providing other conditions of the test are similar. For

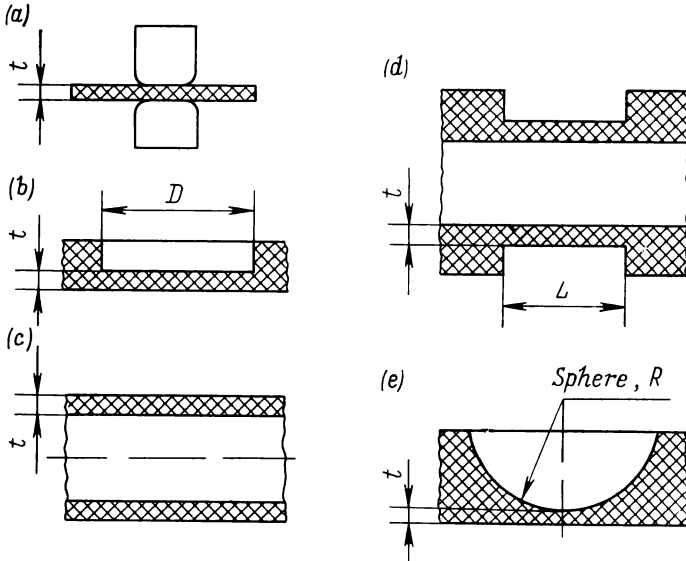


FIG. 5.2. Specimens of solid insulating materials

(a) flat; (b) flat, with rectangular cutout; (c) tubular; (d) tubular, with groove; (e) flat, with spherical recess

estimating the breakdown strength of a material ruptured in a nonuniform field, one should introduce a correction factor $\alpha > 1$. The breakdown strength in this case becomes

$$E_{br} = \frac{U_{br}}{t} \alpha \quad (5.3)$$

The value of α varies with the shape and size of electrodes and interelectrode distance. Thus the electric field produced in solid specimens with spherical sockets of radius R (see Fig. 5.2) or the field in a liquid between dome-shaped electrodes of radius R (see Fig. 5.6) may be regarded as being close to uniform if the distance t is small, for example, equal to $(2 \text{ to } 2.5) \times 10^{-3} \text{ m}$, as is commonly the case in

practice. The condition $t < 2R$ is always met here, providing Eq. (5.3) holds.

The two-electrode system with both electrodes (spheres) ungrounded is called symmetrical in distinction to an asymmetrical electrode system where one of the spheres is grounded. For spherical electrodes (the field being symmetrical)

$$\alpha = 0.25 \left[\frac{t}{R} + \sqrt{\left(\frac{t}{R} + 1 \right)^2 + 8} \right] \quad (5.4)$$

For example, at $R = 25 \times 10^{-3}$ m and $t = 2.5 \times 10^{-3}$ m,

$$\alpha = 0.25 \left[\frac{2.5 \times 10^{-3}}{25 \times 10^{-3}} + 1 + \sqrt{\left(\frac{2.5 \times 10^{-3}}{25 \times 10^{-3}} + 1 \right)^2 + 8} \right] = 1.03 \quad (5.5)$$

The value of breakdown voltage depends on the manner in which the voltage applied to the test specimen rises, smoothly or in steps. In the first case the voltage must grow uniformly from zero so that the breakdown can occur 10 to 20 s after the voltage has started to rise. This test procedure demands certain information on the material under study or, if this not available, requires performing one or two preliminary tests. The rate of voltage rise is specified in the standard for a material.

In tests carried out with a stepwise voltage increase, at every step the voltage is held constant for 1 min. At the first step the voltage is raised smoothly to $0.5U_{br}$, measured in the stepless procedure. On passing from one step to the next, the voltage should rise by one-tenth the value kept at the first step. In this manner, the voltage at the second step must build up to $0.55U_{br}$, at the third step to $0.6U_{br}$, and so on. The time required to pass from one step to the next must not exceed 10 s. Should breakdown take place while passing from one step to the other, the voltage in the preceding step is taken as the breakdown voltage. It is also possible to employ another procedure based on the specified values for the first step in the following range: 0.5, 1.0, 2, 5, 10, 20, 50, or 100 kV. From these values, we choose the one which approximates four-tenths the breakdown voltage estimated in the stepless procedure. The voltage is now raised in steps by 0.1 of the test voltage set up for the first step and

held invariable with each increase for 20 s. The switching period from step to step should be within 2 s, and the total test time not less than 120 s, otherwise the test instructions must specify a lower voltage for the first step. In a.c. tests, the breakdown voltage is commonly expressed as the effective voltage. The way in which the test voltage is to be raised, continuously or in steps, is prescribed in the standard or test specifications on the material.

The breakdown voltage for a material is measured at an alternating current of commercial frequency (50 Hz) and higher frequencies, and also at impulse and direct currents.

The error in measuring the breakdown voltage by either of the methods must be within 4%. The d.c. test voltage must not fluctuate above 5% of the effective value.

The 50-Hz and d.c. breakdown strength E_{br} for solid and liquid electrical insulating materials is determined according to Soviet State standards 6433.3-71 and 6581-75 respectively.

5.2. Specimens and Electrodes

Specimens and electrodes intended for measuring E_{br} of solid materials must have such dimensions as to rule out possible occurrences of surface breakdown. The surface of specimens must be free from fissures, cracks, dents, scratches, and contaminants. The breakdown strength of materials is determined on two types of specimen.

The quantity E_{br} in the direction perpendicular to the surface or layers of materials (laminates) is estimated on flat, shaped, tubular, and band specimens (Fig. 5.2). Flat disc-type specimens shall be 25 to 150 mm in diameter; for square specimens this parameter relates to the side of the square. Tubular specimens are allowed to be 100 to 300 mm in length. The standards do not set limits on the diameter of tubular specimens, but prescribe the shape and dimensions given above; if the standard does not specify the dimensions, one should take the largest. Where the thickness of specimens is too large to determine the dielectric strength at right angles to the surface, shaped specimens (Fig. 5.2*b* and *d*) are applicable. The dielectric strength of ceramic materials

is estimated on specimens with spherical sockets (Fig. 5.2e). The radius R of a spherical recess shall be 12.5 mm and the thickness t of a specimen in the thinnest portion 1 or 2 mm.

Band specimens are pieces of band or tape 15 to 35 mm wide, the length being taken in compliance with the length of the electrode strip.

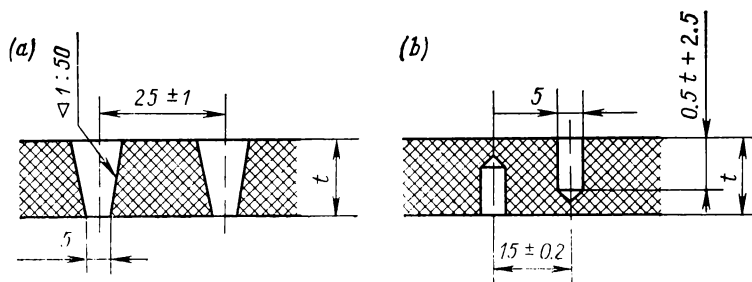


FIG. 5.3. Specimens for determining E_{br} along the layers of solid material

(a) with through holes; (b) with blind holes

The varnish specimens are films deposited on a paper or metal plate substrate, the type of substrate being specified in the appropriate standard.

The specimens used for determining E_{br} in the direction parallel to the surface of a material or along its layers have the shape of plates measuring not less than 60 by 65 mm, each being provided with two through holes or several blind holes (Fig. 5.3). For better grinding-in of electrodes, the through holes are made conical in shape.

Specimens must be measured before tests. The measurement error in thickness t shall not be in excess of $\pm (0.01 t + 0.002)$ mm. The thickness spread shall be within 2% at $t \geq 0.5$ mm and 5% at $t < 0.5$ mm.

Electrodes for testing solid dielectrics must comply with common requirements (see Sec. 1.2). Tests for breakdown strength can be made with massive metal electrodes, film electrodes deposited by sputtering or fusion, and graphite electrodes. In all cases good contact should be provided between the electrode and test specimen. Materials for some

TABLE 5.1

Electrodes for Determining Breakdown Strength

Electrode material	Methods for securing contact with specimen	Type of material tested
Stainless steel, copper, brass, silver, gold	Clamping under pressure whose value is given in the standard on a material; if it is not specified, the pressure must be 10 kPa	All solid materials
Annealed aluminum, tin and lead foil 0.005 to 0.020 mm thick	Rolling and pressing on to a specimen coated with a thin layer of petrolatum, transformer oil, capacitor or petroleum jelly, silicone liquid, grease, or any other similar adhesive	All solid materials not reactive toward the mentioned oils and liquids
Silver, platinum, gold, copper, aluminum	Depositing by vacuum sputtering	Materials that do not change their properties in the given method of electrode deposition
Suspension of colloidal graphite in distilled water	Brushing with subsequent cooling in air	Dense materials
Graphite suspension in epoxy varnish, shellac, cellulose nitrate varnish, etc.	Spraying with air jet. Brushing	All solid materials immune to solvents found in varnishes
Graphite powder	Pouring and compressing	Tubes
Tap water	Immersing or pouring over	Water-resistant tubes

electrodes used in practice and methods of making contact with specimens are given in Table 5.1 (according to Soviet State standard 6433.3-71).

Flat specimens are clamped between two cylindrical electrodes with rounded edges. In order that the field should be

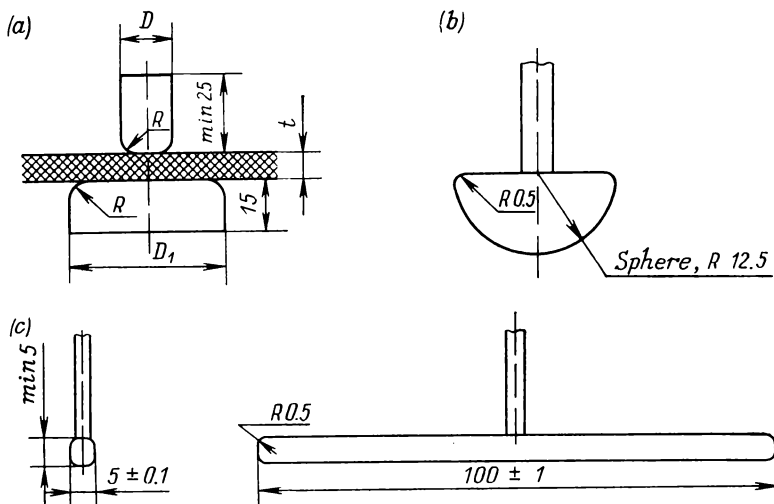


FIG. 5.4. Electrodes

(a) cylindrical; (b) semispherical; (c) strip-type

as uniform as possible, the diameter of the lower electrode, D_1 , must be at least thrice the diameter of the upper electrode D (Fig. 5.4a). The larger electrode is connected to a grounded terminal of the test transformer secondary; if both ends of the secondary are insulated from ground, then the larger electrode is connected to the terminal whose potential approaches the ground potential. The height of a high-voltage electrode also has a substantial effect on the field distribution in a material; it must be at least ten times as large as the thickness of the material under test, but not less than 25 mm. The diameter D of the upper electrode can be equal to 10, 25, and 50 mm. Electrodes of the same diameter can also be used.

Sputtered-on or fired-on electrodes are applicable for flat, tubular, or shaped specimens, in particular for specimens with spherical sockets. The materials for film electrodes obtained by deposition are silver, gold, platinum, copper, or aluminum. Metals are deposited by shooping or sputtering in a vacuum with the pressure reduced to not less than 0.1 Pa. Silver can be applied to ceramic, mica, and glass specimens by the firing process, too.

Graphite electrodes can be produced from the suspension of powdered graphite in an epoxy varnish, shellac, and other varnishes; the suspension is applied on the surface of specimens with a brush or by spraying with an air jet. Graphite-varnish electrodes can be deposited on materials which do not react with the solvent contained in the varnish. Such electrodes are suitable for determining E_{br} of flat, tubular, shaped specimens, and, in particular, of specimens with sockets. Natural-graphite electrodes are produced by compacting the graphite powder in molds, thus giving a graphite coat in the confined areas on flat sheets and tubes. Contact with electrode films deposited into the sockets of specimens is effected by using semispherical metal electrodes 10, 25, or 50 mm in diameter, depending on the radius of a socket (Fig. 5.4b).

For determining E_{br} of materials on tubular specimens, the length L of an outer electrode shall be 10, 25, or 50 mm. A metal tube or film deposited by shooping, sputtering, or firing can be suitable for use as an outer electrode; it is also allowable to produce this electrode from a suspension of powdered graphite in varnish. The inner electrode must be longer than the outer electrode. A straight rod or wire inserted into the tube with a tight fit, or aluminium foil, can do well as an inner electrode.

In determining the dielectric strength of varnish films applied on metal substrates or on compounds molded in metal trays, the substrates or trays act as lower electrodes; the diameter of upper electrodes is the same as that for flat specimens (that is, 10, 25 or 50 mm). The dielectric strength of materials in the form of tape, band, or strip is determined with the use of strip electrodes (Fig. 5.4c) which have the shape of rectangular plates measuring 5 by 100 mm.

For heterogeneous materials, E_{br} is estimated both per-

pendicular and parallel to the surface of a specimen; for laminates, E_{br} is measured along and across the layers using conical pin-type 5-mm diameter electrodes with a taper 1 : 50 (Fig. 5.5a). The electrode ends should extend not less than 2 mm from the surface of the specimen. If surface breakdown inevitably occurs in testing, it is permissible to use the electrodes shaped as shown in Fig. 5.5b. These are two cylindrical pins 5 mm across and not less than 50 mm long tightly fitted into blind holes drilled at a distance of 15 mm one from the other. The end faces of the electrodes have the shape of a semisphere. The electrodes are provided with vents running lengthwise.

The breakdown strength E_{br} of liquid electrical insulating materials is measured on samples taken from each batch of the material being tested. The voltage U_{br} is measured in a special cell (Fig. 5.6), which is a vessel 1 with electrodes 2 built into its walls. The vessel must be made from a material which does not dissolve in test liquids, nor affect their properties. The materials best suited for the purpose are electrical insulating glass and plastic, and also quartz. The electrodes are made from brass shaped like a sphere 25 mm in radius. They must be so aligned that the common axis should run parallel to the cell bottom. The interelectrode gap is 2.5 ± 0.05 mm. The depth of electrode immersion into a test liquid shall be not less than 40 mm, and the distance from the electrode surface to the cell walls not less than 12 mm. The design of the cell must allow for ease of its dismantling and removal of the electrodes for cleaning and polishing.

Prior to pouring a test liquid into the cell to initiate tests, it is necessary to dry, clean and then thoroughly rinse the cell with the test liquid. The liquid should be poured slowly to allow air bubbles to escape freely.

The test for breakdown voltage U_{br} is repeated not less than 6 times. For liquids with a viscosity of less than 50×10^{-6} m²/s (50 cSt), all measurements are taken on a single sample. For liquids with a viscosity over 50×10^{-6} m²/s, the cell should be refilled after every measurement.

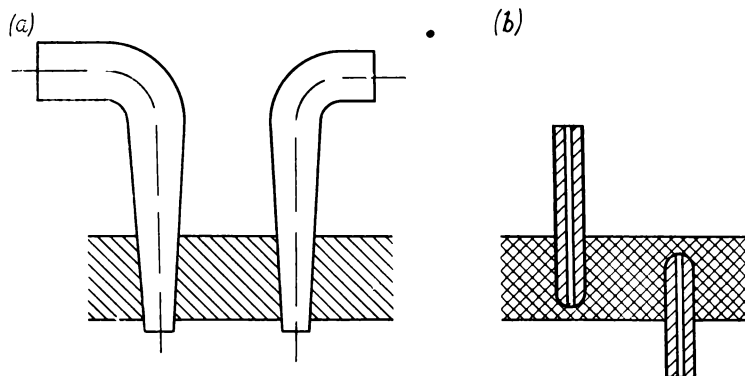


FIG. 5.5. Electrodes for determining E_{br} along the layers of solid material

(a) conical; (b) cylindrical

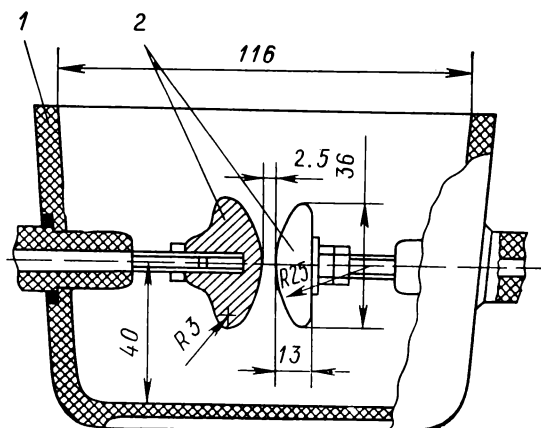


FIG. 5.6. Cell for measuring U_{br} of liquid dielectrics

5.3. Measuring U_{br} at 50 Hz

A test unit, as shown in Fig. 5.7, for measuring U_{br} consists of a device 1 for stepless voltage control, a test step-up transformer 2, a chamber 5 for a test specimen 3 furnished with electrodes, and other elements. The voltage control

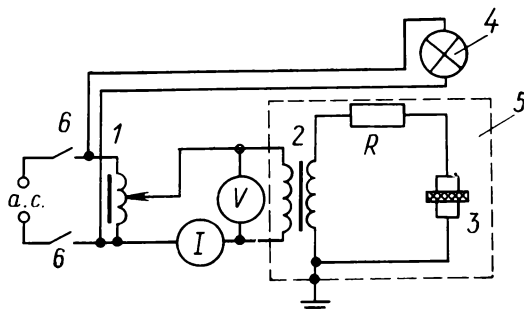


FIG. 5.7. Circuit diagram for measuring U_{br} at a.c. voltage

device should secure a continuous variation in voltage so that its changes cannot exceed 5% of the transformer voltage rating. It is preferable to increase voltage automatically. The power of the test unit must be sufficient to keep the effective steady-state short-circuit current on the H.V. side not less than 40 mA in testing solid dielectrics and not less than 20 mA in testing liquid dielectrics. The transformer primary includes an automatic cutout 6 to interrupt the circuit after specimen breakdown and an indicating lamp 4.

As mentioned above, the test unit incorporates a device for stepless voltage increase that must meet a number of requirements. The power source, voltage control device, and transformer must secure a sinusoidal waveform of voltage impressed on the specimen; the crest factor of the test voltage (the ratio of the peak voltage to the rms voltage) must be of the order of 1.34 to 1.48. The frequency must be kept at 50 Hz, the permissible deviation being ± 0.5 Hz. Besides, the voltage control device should be rated at the required power, be simple in design and reliable in service.

Test units usually employ static voltage regulators such as a variable resistor, autotransformer, adjustable-ratio

autotransformer, and induction voltage regulator (Fig. 5.8). Where the test transformer has a small power (up to 1 kV A), a variable resistor 2 connected in the circuit as shown in Fig. 5.8a can be used to adjust the voltage. It is impermissi-

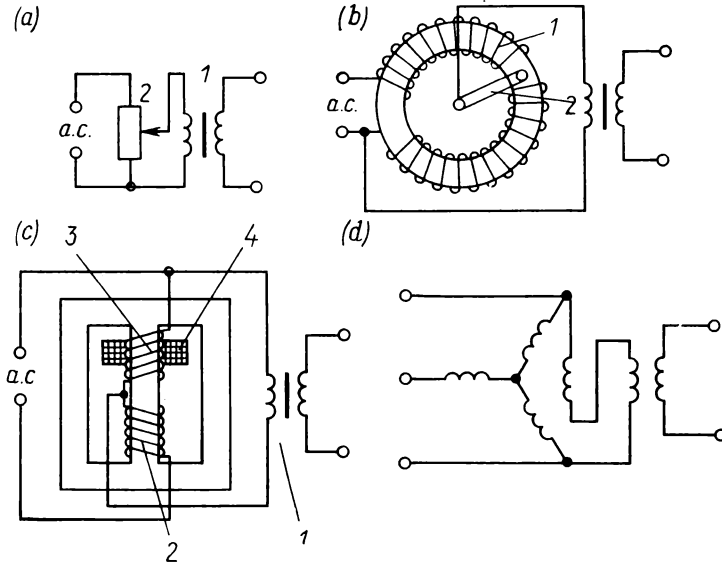


FIG. 5.8. Circuit diagrams of static voltage regulators
 (a) resistance-type; (b) and (c) transformer-type; (d) induction-type

ble to control voltage with the series-connected resistor since this causes excessive voltage waveform distortion as the magnetizing current of a transformer 1 flows through the resistor. A laboratory autotransformer (Fig. 5.8b) secures a comparatively smooth voltage variation under load. The transformer winding 1 is bare at the place where a sliding contact 2 moves across the turns. The contact arm has a small width, so it shorts out only one or two turns. Since the voltage on a single turn is small, while the contact resistance between the copper wire and the arm is high, the current that passes through the short-circuited turns and the arm is too low to overheat the contact. The transformer winding has a large number of turns so that changes in voltage as the

arm slides over the turns are insignificant. Along with a small waveform distortion and low power loss, another feature of autotransformers is that they can step up voltage drawn from the supply line. The voltage varies linearly with the motion of the arm, which enables a uniform voltage adjustment. Autotransformers come in various power ratings, up to a few kilovolt-amperes. They are designed for intermittent-operation to allow the winding and the sliding contact to cool down in idle intervals.

Another method of voltage control uses an autotransformer with a movable short-circuited coil 4 sliding on a core that also carries two windings 2 and 3 connected in opposing relationship (Fig. 5.8c). A high-voltage test transformer is connected to the winding 3. When the coil is in the upper position, the magnetic flux traversing the winding 3 is small, the electromotive force induced in the winding insignificant, and the voltage at the input of the test transformer is close to zero. In this case all the voltage of the supply line is mainly applied to the winding 2. If the coil 4 shifts to the lower most position, the magnetic flux across the winding 2 becomes weak. The source voltage is now impressed on the winding 3, and the voltage at the input of the test transformer is at a maximum. The coil 4 shifted along the core causes the voltage to vary in a stepless manner from zero to the supply line voltage. Voltage regulators with a movable coil show low power loss and do not practically distort the waveform of the voltage source. They are available in power ratings from tens to hundreds of kilovolt-amperes.

One more method of voltage control utilizes an induction voltage regulator (Fig. 5.8d). An example of the simplest induction regulator may be a braked induction motor with a polyphase rotor. The design of the motor is such that the rotor can be smoothly turned through 180° . The three-phase source supplies power to three windings of either the stator or rotor, which produce a rotating field. If it is the rotor, the rotating field induces an alternating voltage in every stator winding. As the rotor is turned, the amplitude of this voltage remains invariable, while its phase changes. The primary of the test transformer is connected to the power source in series with one of the above mentioned phase windings. The transformer is thus furnished with a voltage

which is a geometrical sum of supply line voltage U_1 and phase winding voltage U_2 . Depending on the position of the rotor, the shift in phase between the voltages U_1 and U_2 will be different in magnitude. So, as the rotor turns, the voltage in the transformer primary, U_{tr} , will smoothly vary from a minimum ($U_1 - U_2$) to a maximum ($U_1 + U_2$). Induction voltage regulators effect a continuous voltage adjustment, but they cause waveform distortion.

Motor-driven voltage regulators have recently become popular, in which an electric motor complete with a reduction gear moves the autotransformer brush holder or turns the rotor, thereby increasing the voltage at a preset rate.

A short-circuit current that flows through a specimen at the moment of its breakdown can heavily overload the transformer. To guard against this current, the transformer must have a protection device on its L.V. side to disconnect the power source after rupture of the specimen. The operating time of this device must not exceed 0.02 s.

It is particularly important to promptly deenergize a measuring cell in testing liquid materials because in some of the liquids the first breakdown initiates material disintegration. The products of decomposition heavily decrease the breakdown strength of the test liquid in the next series of breakdown tests. This feature is inherent in synthetic liquid materials based on chlorinated aromatic hydrocarbons, silicone substances, and others. In testing these materials, the breakdown test period should be short enough to disregard the effect of material decomposition.

Figure 5.9 shows a circuit diagram of a test unit with an arrangement that rapidly switches off the source of voltage impressed on a test liquid after its breakdown. The unit has a cell 4 for a test liquid, electrodes 5 fed with voltage from a regulating transformer 3 through a step-up transformer, and a sphere gap 1 placed in parallel with the cell. The distance between the electrodes of the sphere gap varies in step with changes in the voltage of the regulating transformer. The interelectrode distance is not sufficiently large for the arc discharge to build up but enough to keep the arc steady whenever it appears. Apart from its main electrodes, the sphere discharger has a trigger electrode 2. At the moment of breakdown of the test liquid, a breakdown current passes

through a resistor $R3$ that causes a voltage drop across it. This voltage applied to the trigger electrode through a resistor $R4$ initiates a disruptive discharge across the trigger gap. The voltage across the discharger then drops off to a value insufficient for the repeated breakdown of the test liquid.

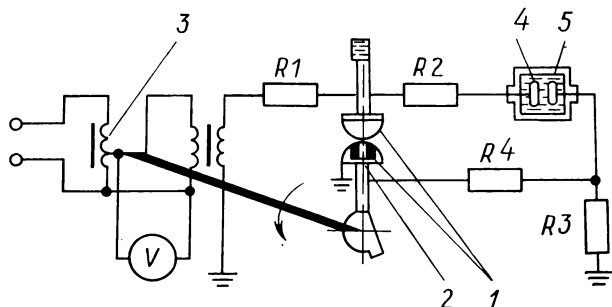


FIG. 5.9. Circuit diagram of a test unit providing fast disconnection of power supply from test liquid after breakdown

In testing solid dielectrics a disruptive discharge disables the test specimen and necessitates its replacement by a new one. The high-voltage circuit contains a protective resistor R in series with the specimen (see Fig. 5.7), which limits the short-circuit current. The choice of R depends on the dynamic stability of the transformer; if the data on transformer stability is not available, the value of R is taken to equal 0.2 to 1 ohm times the high voltage on the H.V. side, if the rated voltage does not exceed 110 kV. It is desirable to measure breakdown voltage on the H.V. side using for the purpose a kilovoltmeter, low-voltage voltmeter with a voltage transformer, and sphere gap. Measurements can also be taken on the L.V. side of the test transformer with a voltmeter calibrated against a sphere gap or kilovoltmeter.

A sphere gap can function as an instrument for measuring breakdown voltage, since this voltage varies in a definite manner with the distance between the spheres of a given diameter. The error in the measurement of voltage amplitude shall be within $\pm 3\%$. There are symmetrical and asymmetrical systems of connection of spherical electrodes (Fig. 5.10a and b).

The breakdown voltage for air between the spheres is found from Table 5.2 which gives breakdown voltages with respect to the diameter of and distance between the spheres under normal test conditions. From this table it is clear

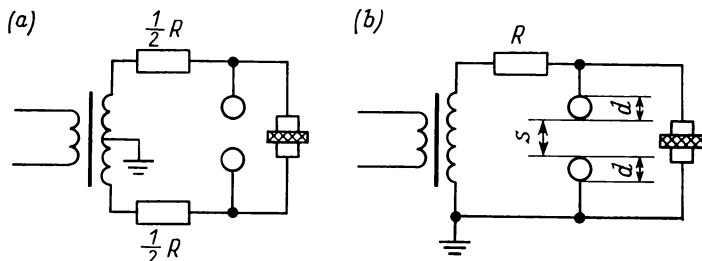


FIG. 5.10. Symmetrical (a) and asymmetrical (b) circuits of connection of spherical electrodes

that at a distance over 1 cm between the spheres, the breakdown voltage for the symmetrical voltage distribution (both spheres being insulated) is somewhat higher than for the case of the asymmetrical system (one sphere grounded). With the asymmetrical connection of electrodes, the d.c. breakdown voltage also depends on the polarity of the ungrounded sphere.

Where test conditions differ from the normal, one should introduce the correction factor a to allow for the deviation of tabulated breakdown voltages from the true values:

$$U_{br} = aU_0$$

where U_0 is the breakdown voltage at $p = 101.3$ kPa (760 mm Hg) and $t = 20^\circ\text{C}$. The correction factor a depends on the relative density of air, δ :

δ	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10
a	0.72	0.77	0.81	0.86	0.91	0.95	1.00	1.05	1.09

With changes in relative density of air from 0.95 to 1.05, the correction factor a becomes equal to δ .

Using sphere gaps, it is possible to calibrate a test transformer, that is, to determine the transformation ratio as a function of voltage. This calibration is made with a sphere gap and voltmeter connected in the circuit either on the L.V. side of the test transformer or across the instrument trans-

TABLE 5.2

Breakdown Voltage (Amplitude Values in Kilovolts) for Sphere Gaps at Commercial Frequency Under Normal Test Conditions ($p=101.3$ kPa, $t=20^{\circ}\text{C}$)

Intersphere gap, <i>s</i> , cm	Symmetrical connection*					Asymmetrical connection**						
	Sphere diameter <i>d</i> , cm											
	2	5	6.25	10	12.5	15	2	5	6.25	10	12.5	15
0.05	2.4	—	—	—	—	—	2.4	—	—	—	—	—
0.1	4.4	—	—	—	—	—	4.4	—	—	—	—	—
0.15	6.3	—	—	—	—	—	6.3	—	—	—	—	—
0.2	8.2	8	—	—	—	—	8.2	8	—	—	—	—
0.3	11.6	—	—	—	—	—	11.5	—	—	—	—	—
0.4	14.9	14.3	14.2	—	—	—	14.8	14.3	14.1	—	—	—
0.5	18.1	—	—	16.9	16.7	16.5	18	—	—	16.9	16.7	16.5
0.6	21.2	20.4	20.2	—	—	—	21	20.4	20.2	—	—	—
0.7	21.4	—	—	—	—	—	23.9	—	—	—	—	—
0.8	26.9	26.4	26.2	—	—	—	26.6	26.3	26.1	—	—	—
0.9	29.5	—	—	—	—	—	29	—	—	—	—	—
1.0	32	32.2	32	31.6	31.5	31.3	31.2	32	31.9	31.6	31.5	31.3
1.2	36.7	37.8	37.6	—	—	—	35.1	37.6	37.5	—	—	—
1.4	41.2	43.3	43.2	—	—	—	38.5	43	43	—	—	—
1.6	45.2	48.5	48.6	—	—	—	41.4	48.1	48.4	—	—	—
1.8	47.8	53.5	53.9	—	—	—	44	53	53.6	—	—	—
2.0	51.2	58.3	59	59.3	59.4	59.2	46.2	57.5	58.2	59.1	59.2	59.2
2.4	—	67.3	68.6	—	—	—	—	65.3	67.4	—	—	—
3.0	—	79.3	81.8	84.9	85.4	85.8	—	75.4	79.1	84.1	85.2	85.5
3.5	—	88.3	91.8	96.5	97.7	98.4	—	82.4	87.5	95.2	97.2	98.1
4.0	—	96.4	101	107	110	111	—	88.4	94.8	105	109	110

* Data also relate to d.c. test voltage irrespective of the sign of potential applied to the spheres.

** Data also refer to d.c. test voltage with the negative potential applied to the ungrounded sphere; for the positive potential, V_b is somewhat higher if the interelectrode gap is over 1.2 cm.

former. When measuring voltage with sphere gaps, these should be placed away from the objects that are prone to distort the field between the spheres and introduce an error in the measurement. The distance from the walls and current-carrying objects to the spheres must be at least seven times the sphere diameter. A series resistor connected in the circuit serves as a current limiter in case of sphere gap breakdown.

It is advisable to calibrate a transformer with a sphere gap whose interelectrode space does not exceed three-fourths the sphere diameter. The calibration is generally performed with the test object connected to the transformer, because the capacitance (over 1 000 pF) and, sometimes, the insulation resistance of the object under test may have an influence on the transformation ratio. This ratio also depends on voltage, for which reason the transformer should be calibrated over the voltage range from a minimum value to the nine-tenths of the discharge, or breakdown, voltage.

5.4. Measuring U_{br} at Direct Current

The circuit diagram of a test unit (Fig. 5.11) is principally the same as shown in Fig. 5.7, but its high-voltage circuit contains a rectifier unit; the capacitor C connected across

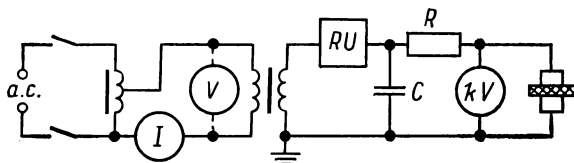


FIG. 5.11. Circuit diagram of a test unit for measuring U_{br} at d.c. voltage

the circuit smoothes out ripples. Though specifications permit the ripple that does not exceed 5% of the crest value, the available rectification circuits ensure a much lower level of fluctuations. The rectifier unit RU consists of a rectifier proper, either of the vacuum-tube or of the semiconductor type, a filter, and, in some cases, a multiplying circuit for the rectified voltage. Rectifiers are commonly

high-voltage hot-cathode high-vacuum tubes (kenotrons) or semiconductor diodes.

A few rectification circuit diagrams have found extensive applications, in which parallel-connected capacitors serve as smoothing filters to remove fluctuations in the

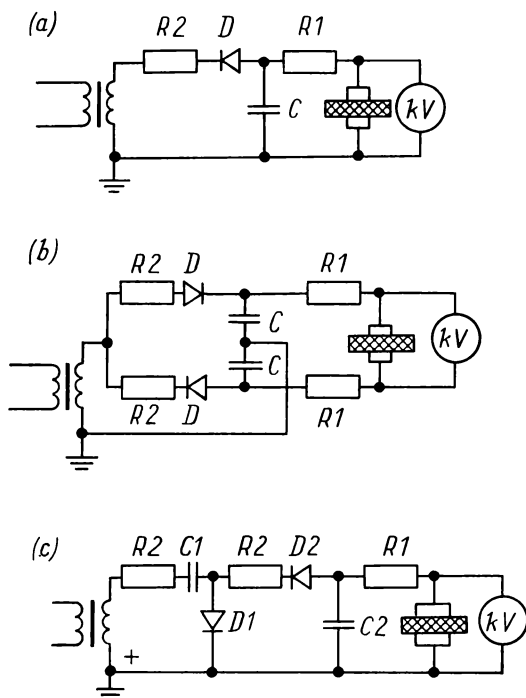


FIG. 5.12. Half-wave voltage rectification circuit (a) and voltage doubler rectification circuit (b, c)

output current. At voltages close to 50 kV, one can use a half-wave rectifier network (Fig. 5.12a). At higher voltages, however, the test unit should have a voltage multiplier with two rectifiers (Fig. 5.12b). Here one capacitor charges through a rectifier during the first half cycle of voltage, and the other through the second rectifier during the next half cycle of reversed polarity. Every capacitor

charges to a voltage U_{tr} , equal to about the peak value of voltage on the transformer secondary. The specimen is fed with a direct voltage (symmetrical with respect to ground), whose value is approximately equal to a twofold peak value of voltage in the transformer secondary winding. In actual fact, the applied voltage is lower than $2U_{tr}$, because of partial discharge of the capacitors due to a flow of leakage current.

The voltage doubler circuit can also be of the asymmetrical type (Fig. 5.12c). At that half cycle when the rectifier $D1$ lets the current pass through, the capacitor $C1$ charges, while the rectifier $D2$ cuts off the circuit; the capacitor $C1$ charges to the peak amplitude of the transformer voltage U_{tr} . In the second half cycle, the rectifier $D2$ becomes conductive and the capacitor $C2$ charges at a voltage equal to about $2U_{tr}$, taken off the transformer winding and capacitor $C1$ connected in series.

The asymmetrical type of circuit can be used to make tests on specimens provided with one grounded electrode and also on single-pole grounded insulation elements such as bushing insulators.

In these circuits the resistances and capacitances must have such values that the voltage ripple cannot exceed 5% of the peak value. In the half-wave rectifier network shown in Fig. 5.12a, at a capacitance of the capacitor equal to 0.001 mF, the ripple does not go above 2% of the peak value if the insulation resistance of a specimen is not below $10^9 \Omega$ and, besides, other components of leakage current are negligible.

The breakdown voltage is usually measured on the H.V. side with an electrostatic kilovoltmeter or a sphere gap. The voltage can also be measured on the L.V. side with a voltmeter, calibrated against a sphere gap, placed in parallel with a specimen. It is desirable to calibrate the voltmeter when the rectifier unit operates in the steady state, with the specimen connected in the circuit.

5.5. Measuring U_{tr} at Impulse Voltage

In some cases materials and components are subjected to impulse voltage tests. Among voltage impulses, consider the test impulses of the lightning surge type and switch-

ing voltage type. Fig. 5.13 illustrates the first type of surge voltage waves. The full wave impulse has an aperiodic shape shown in Fig. 5.13a. The portion OF on the impulse wave is the impulse wavefront of a certain duration. In practice it is difficult to determine for sure the origin of the

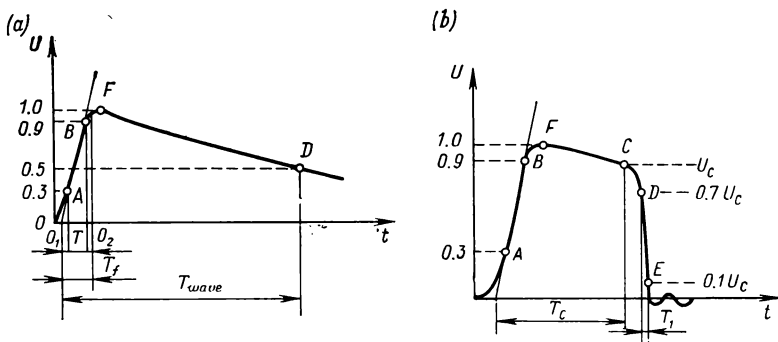


FIG. 5.13. Surge voltage waves

(a) full impulse voltage; (b) impulse voltage chopped on the tail

wave and the instant when the impulse voltage has reached its peak value (at F). For this reason the virtual front time T_f is estimated as follows. Plot on the voltage-time graph two points A and B representative of 30% and 90% of the peak value and draw through these points a straight line until it intersects the X -axis and the straight line corresponding to the amplitude of the wave. The point of intersection, O_1 , is the virtual origin (zero time) of the wave. The intercept on the X -axis between the points O_1 and O_2 gives the wave-front duration T_f which is 1.67 times larger than the time T taken by the voltage to increase from 30% (point A) to 90% (point B) of its peak value. From the point F the impulse begins to collapse. The impulse wave duration T_{wave} is the time interval between the virtual zero point O_1 and the instant when the voltage on the wavetail has decreased to half its peak value (at D).

The lightning surge impulse chopped on the tail is displayed in Fig. 5.13b. The impulse of such a shape has two more characteristics along with those mentioned above.

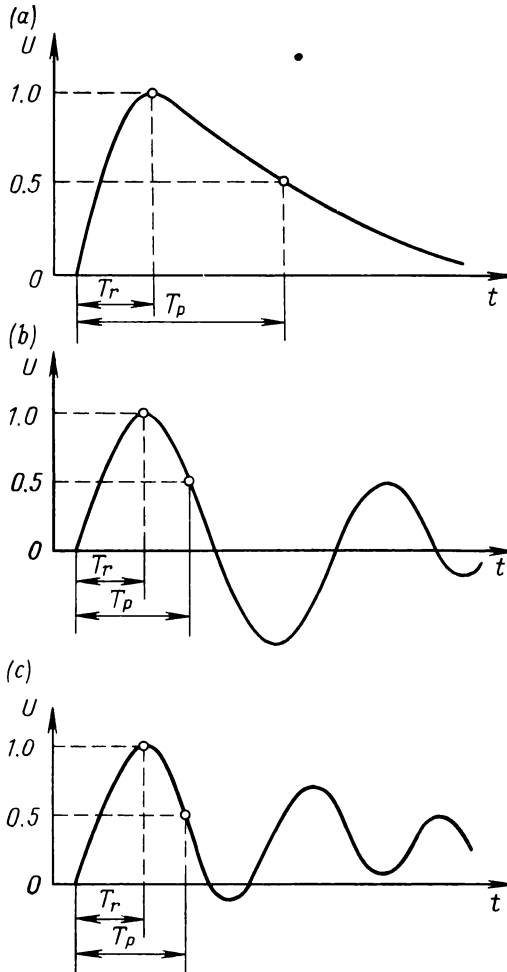


FIG. 5.14. Switching impulse voltage waves
(a) aperiodic; (b) and (c) oscillatory

These are the time to chopping and the time of voltage collapse during chopping. The time to chopping T_c is the time interval between the virtual origin of the wave and the

instant of chopping (at C). The chopping time is 1.67 times the time interval T_1 between reference points D and E

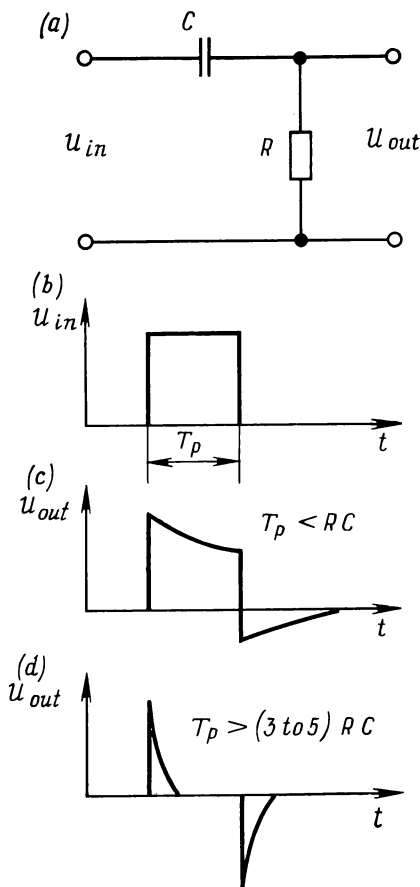


FIG. 5.15. Differentiating circuit (a) and pulse shapes at input (b) and output (c, d)

and pulse width T_p . The standard aperiodic pulse has T_r of $(250 \pm 50) \mu s$ and T_p of $(2 \text{ } 500 \pm 500) \mu s$. In testing specimens with switching voltage pulses, the peak value of a pulse is taken as the test voltage. The break-

at which the chopped impulse voltages on the wavetail are respectively equal to 70% and 10% of the voltage U_c at the instant of chopping.

Impulses can be of both positive and negative polarity. The standard full wave impulse must have the following parameters: the front time $T_f = (1.2 \pm 0.36) \mu s$ and impulse wave length $T_{wave} = (50 \pm 10) \mu s$, with the peak value varying within $\pm 3\%$. The standard designation of such an impulse is 1.2/50, where the numerator gives T_f and the denominator T_{wave} . The standard chopped wave impulse is the full wave impulse with the time to chopping, T_c , equal to 2 to 5 μs .

Switching impulse voltage can be of the aperiodic type (Fig. 5.14a) and the oscillatory type (Fig. 5.14b and c). The basic parameters for these pulses are the front duration, or rise time, T_r ,

down voltage U_{br} is assumed to be the peak value of the voltage wave if the breakdown has occurred at its maximum or a little later on the wavetail. If the breakdown takes place on the front of the wave, the value noted at the instant is considered the breakdown voltage.

The impulse sources used in testing are special impulse generators. The generator of this type is mainly a sine-wave or square-wave generator with a shaper intended to give a surge of the desired wave shape. The shaper is a passive RC or RL network with circuit components arranged in any desired manner to perform the function. In wide use are differentiating and integrating circuits.

Figure 5.15a shows a differentiating resistance-capacitance network. The voltage u_{out} at the output of such a circuit is related to the input voltage u_{in} through an expression

$$u_{out} = u_{in} - u_C$$

where u_C is the voltage across a capacitor. Expressing the voltage across the capacitor through the current i , we may write

$$u_{out} = u_{in} - \frac{1}{C} \int i_C dt$$

Differentiating the right and the left side of this equation and considering that $i = u_{out}/R$, we obtain

$$\frac{du_{out}}{dt} = \frac{du_{in}}{dt} - \frac{du_{out}}{RC}$$

whence

$$u_{out} = RC \frac{du_{in}}{dt} - RC \frac{du_{out}}{dt}$$

In the right side of the equality, the first term is proportional to the derivative of the input voltage, the second term being an error in differentiation. To decrease this error, the following condition must be met: $u_{out} \ll u_C$, that is, $R \ll 1/(\omega C)$. Where this is the case

$$u_{out} \approx RC \frac{du_{in}}{dt} = \tau \frac{du_{in}}{dt}$$

that is, the output voltage is proportionate to the derivative of the input voltage. The circuit that does not meet

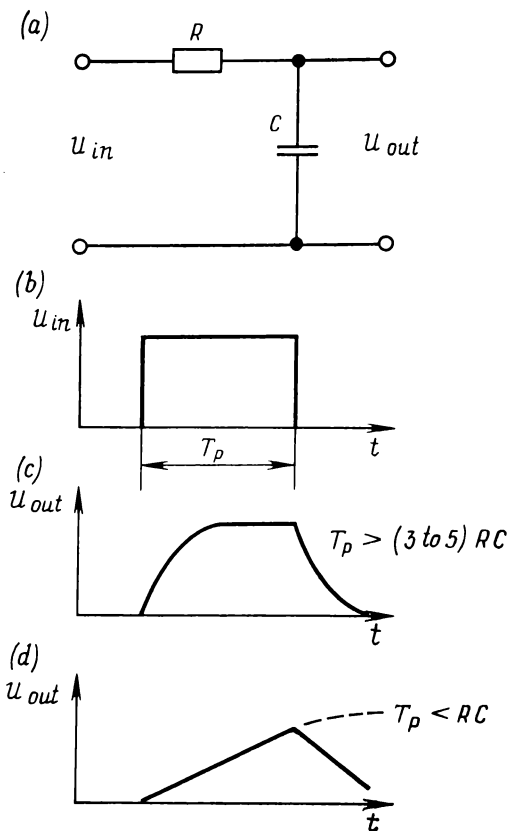


FIG. 5.16. Integrating circuit (a) and pulse shapes at input (b) and output (c, d)

the condition $R \ll 1/(\omega C)$ is called pulse-shortening. Fig. 5.15 illustrates the pulse waveforms derived at the output by applying to the input a square-wave pulse with a varying relation between the pulse length and circuit time constant.

In an integrating circuit (Fig. 5.16a), given definite conditions, the output voltage is proportionate to the inte-

gral of the input voltage

$$u_{out} \approx \frac{1}{RC} \int u_{in} dt$$

For this condition to be fulfilled, the circuit must satisfy the condition $R \gg 1/(\omega C)$. If the latter condition is not clearly met, the integration will be in error. Fig. 5.16c

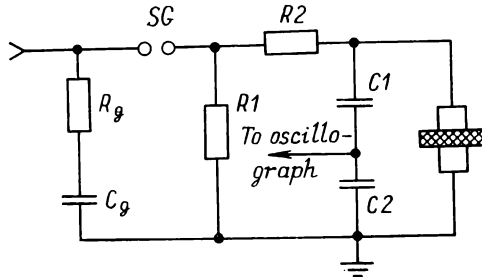


FIG. 5.17. Circuit diagram of a unit for generating aperiodic switching voltage pulses

and d gives the output waveforms shaped by the circuit on applying to its input a square-wave pulse (Fig. 5.16b).

Figure 5.17 shows the circuit diagram of a unit for shaping an aperiodic switching-voltage pulse. The pulses taken off the impulse generator output go across a sphere gap SG and arrive at an integrating circuit composed of a resistor $R2$ and capacitors $C1$ and $C2$ connected in series. To produce an aperiodic voltage pulse, the system is to satisfy the condition

$$R_g + R_2 \approx \frac{1}{3} T_r \frac{C_g + \frac{C_1 C_2}{C_1 + C_2} + C_0}{C_g \left(\frac{C_1 C_2}{C_1 + C_2} + C_0 \right)}$$

where C_0 is the capacitance of a test specimen; R_g and C_g are respectively the resistance and the capacitance in the impulse generating circuit.

The capacitors $C1$ and $C2$, apart from being the elements of the integrating circuit, perform the function of a capacitive voltage divider whose output is fed to an oscillograph to control the pulse waveform. The resistor $R1$ remo-

ves capacitances after breakdown in a specimen. The final choice of the circuit parameters is made from the analysis of voltage waveform records produced by the oscillograph during the adjustment of the impulse generator with the specimen connected in the circuit.

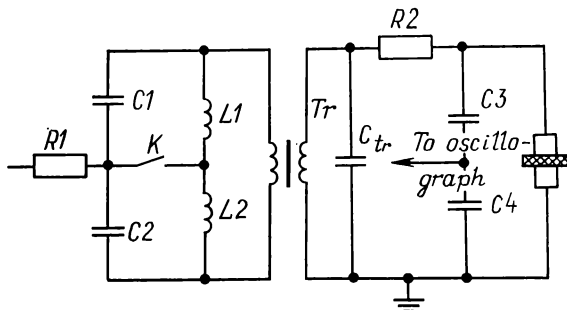


Fig. 5.18. Circuit diagram of a unit for generating oscillatory switching voltage pulses

Consider the circuit of one more unit intended to produce an oscillatory pulse (Fig. 5.18). The basic components of the circuit are two opposing oscillatory networks $L1C1$ and $L2C2$ and also a transformer Tr . The operating principle of the unit is the following. First capacitors $C1$ and $C2$ charge to the same voltage level. After closing the circuit with a switch K , the capacitors begin to discharge through inductors $L1$ and $L2$. The networks $L1C1$ and $L2C2$ differ substantially in natural frequency, so that the primary of the step-up transformer Tr will receive an oscillatory decaying-voltage pulse with a smoothly rising wavefront. The voltage pulse induced in the secondary will certainly have an oscillatory decaying waveform. In this circuit $C3$ and $C4$ make up a capacitive voltage divider; C_{tr} is the capacitance of the transformer secondary.

5.6. Some Features of Electrical Breakdown Tests

The conditions of testing various materials for breakdown voltage U_{br} and breakdown strength E_{br} are prescribed in pertinent standards or specifications.

Determining U_{br} and E_{br} of solid materials. As described earlier, the test voltage can be raised to the breakdown value either uniformly or in steps, depending on the requirements of the standard. Before conducting the step-by-step method of test, one should first estimate U_{br} under the condition of stepless voltage adjustment. The rate of a continuous voltage rise must be such that the breakdown in a specimen can occur 10 to 20 s after the start of voltage increase. In the step-by-step method, the voltage is first raised smoothly to 40% of U_{br} estimated in the stepless test and then increased at 20-s intervals until the specimen fails by becoming conducting. The time of transition from step to step shall be 1 or 2 s. In a.c. breakdown tests, the rms value is taken as a breakdown voltage. Since the scatter in the measured values is rather large, it is desirable to subject to tests as many specimens as possible and then process the test results with statistical methods such as described in Introduction. The standard on a material specifies a minimum number of breakdowns. Knowing the value of U_{br} that has caused a disruptive discharge, we can calculate the breakdown strength for a flat and a tubular specimen by Eqs. (5.1) and (5.2), respectively, and for a specimen with a spherical socket by Eq. (5.3) with the correction factor α taken into account. For a number of solid materials, standards prescribe specific test procedures for determining U_{br} and E_{br} . Consider some examples.

The tests for determining E_{br} of pertinax (paper-base laminate) in a direction parallel to laminations are made on 60 by 65 mm flat specimens of thickness t (Soviet State Standard 2718-74). Each specimen is provided with two 5 mm-dia blind holes on the opposite faces, one on each face, spaced 15 mm apart and drilled to a depth of $(t/2 + 2.5)$ mm to receive two electrodes. The specimen is then immersed into transformer oil to exclude surface discharge. The breakdown voltage is determined by smoothly raising the test voltage.

The breakdown strength of pertinax in the direction normal to laminations is estimated on 100×100 mm flat specimens fitted out with copper electrodes, the lower being 75 mm in diameter and the upper 25 mm. The thickness of a specimen shall be not over 3 mm, otherwise it must be ground

to size on one of its faces. The specimens are tested under transformer oil at 90°C by uniformly increasing the voltage.

The breakdown strength of glass cloth-base laminate in a direction normal to layers is determined after conditioning specimens first at 70°C for 4 h and then at 15 to 35°C at 45 to 75% relative humidity for 6 to 24 h. The measurements are taken at 90°C on 3-mm thick specimens immersed into transformer oil. Before running the tests, the specimens are held in oil at 90°C for 30 min. The electrodes used are flat discs. The test voltage is increased uniformly to breakdown at a specified rate.

The breakdown voltage of textolite (cloth-base laminate) parallel to laminations is determined under the same conditions as given above (at 90°C) using pin-type electrodes to raise the test voltage uniformly until breakdown.

For samica, the breakdown voltage is determined at five points on the surface of a 150 by 300 mm specimen provided with two cylindrical electrodes, the upper being 25 mm in diameter and the lower 75 mm. The voltage is increased uniformly to breakdown at a rate of 0.3 kV/s.

The test of mica tape for breakdown strength is made on specimens preconditioned at 15 to 35°C and 45 to 75% relative humidity for 24 h. Mica tape specimens are a strip or four separate strips 20 mm in width and about 3 m in total length. Electrodes are rectangular plates or rods 6 mm in diameter. A specimen is tested at 10 equidistant points, with the voltage raised uniformly to breakdown.

The breakdown voltage of heat-resistant glass-bonded micanite is determined on specimens dimensioned so as to exclude surface breakdown. The electrodes are flat discs 50 mm in diameter. The measurements are taken at five points, the voltage being raised uniformly.

The breakdown strength of radio ceramics is estimated on flat discs 35 mm in diameter and 1.5 mm in thickness, provided with 8-mm diameter silver electrodes. The test is run under capacitor oil by uniformly increasing voltage across the specimen clamped between 6-mm diameter terminals. The breakdown strength of a ceramic material is determined on at least 10 specimens.

The breakdown voltage of varnished cloth is determined by uniformly raising the voltage applied to two cylindrical

electrodes, each 6 or 50 mm in diameter, pressed against the specimen at 17 or 10 kPa respectively. The measurements are taken at a minimum of 10 points in such a sequence: at 20°C before and after bending the specimen; at 105°C; after 24-h exposure to the humid atmosphere at $(95 \pm 2)\%$ relative humidity at 20°C and then after 18-h heat treatment at 100°C and subsequent bendings of the specimen. Besides, U_{br} is determined on specimens subjected to stretching; the measurements are done at 10 points on two 30×400 mm specimens cut out at 45° to the direction of warp threads, the voltage being raised uniformly. The electrodes are 6-mm diameter rods located one opposite the other and pressed against the specimen at a load of 5 N.

The tests for U_{br} of capacitor paper are made on 0.3-m long paper tape specimens. From each roll, 10 to 15 lengths of paper are taken. The paper samples are dried before test at 105 to 110°C for 3 h and then held in normal conditions at 20°C and a relative humidity of 65% for 6 h. The electrodes are flat discs 10 mm in diameter for paper samples 30 mm wide, and 25 mm for samples over 30 mm wide; the electrodes must be kept at a pressure of 2 kPa. Here, too, the test voltage is increased uniformly. Since in the course of tests carbon usually appears on the electrodes, these should be replaced every 500 breakdowns.

The breakdown voltage of plastics based on styrene copolymers is determined on disc-type specimens 100 mm in diameter and 2 mm in thickness. The specimens are provided with cylindrical stainless steel or brass electrodes 25 mm in diameter. The tests are conducted with the specimens held in transformer oil, the voltage being increased uniformly until rupture.

Determining U_{br} and E_{br} of liquid dielectrics. The method of test involves a uniform increase of voltage from zero to the breakdown value at a rate of 2 kV/s; the rms value is taken as the breakdown voltage. The test procedure calls for at least 6 disruptive discharges on a test liquid. The first breakdown is effected 10 min after filling the cell with the test liquid. The particles of soot formed in the interelectrode gap are removed after each breakdown with a glass rod. While removing the carbon, air may get into the liquid, so one should raise voltage for the next discharge

not earlier than 1 min after the air bubbles have escaped from the liquid. Breakdowns are produced at a minimum of 5-min intervals. If it is difficult to remove soot after each breakdown, as is the case in testing viscous liquids, the cell should be refilled every time the breakdown has occurred, thus making the tests on at least six samples. In this case, the sample to be poured into the vessel should first be heated to the very liquid state and then allowed to cool down to the ambient temperature. The breakdown strength is then calculated by formula (5.1) if the cell has flat electrodes and by formula (5.3) if the cell has semispherical electrodes, the factor α being taken equal to 1.025.

Prior to its testing, capacitor oil is dried at a residual pressure of 133 Pa and 80 to 85°C for 10 h. Two liters of oil are enough to make up the control sample. The test procedure is the same as for other liquid dielectrics.

5.7. Test Units for Measuring U_{br}

There are commercially available units for measuring U_{br} of liquid and solid materials. One such unit, a type АИИ-70 insulation tester (Fig. 5.19), is adaptable both to measuring U_{br} of materials and to testing cable insulation. The unit offers the highest test voltage of 50 kV in a.c. tests and 70 kV in d.c. tests. The high-voltage transformer is rated at 2 kV A.

The supply line feeds voltage through auxiliary contacts and safety devices to a regulating autotransformer $Tr1$ intended for uniform voltage adjustment and to the heater transformer $Tr2$ of a hot-cathode rectifier tube. High voltage is conveyed to the measuring cell by pressing the button of a circuit breaker $K1$ having three coils, of which two are connected in series and one of the two is shunted by a protective switch $K2$. The off position of this switch secures "high-responsive" protection: the circuit breaker does not come into action as breakdown takes place on the a.c. side and remains closed as long as the rectified current does not exceed 5 mA. The on position of the switch $K2$ secures "low-responsive" protection: the circuit breaker does not operate in case of short-circuit on the high-voltage side and

remains closed if the power on the high-voltage side (at 50 kV) does not exceed 2 kV A; this condition must persist for not more than 1 min. The voltage across a specimen is measured on the low voltage side with a 1.5 accuracy class voltmeter *kV* calibrated in kilovolts. Capacitors serve to

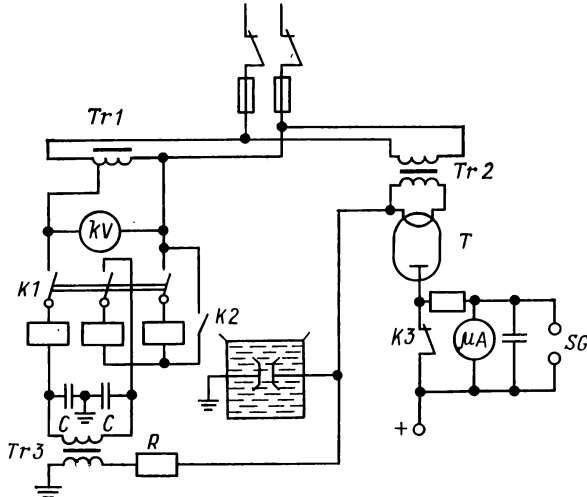


FIG. 5.19. Circuit diagram of type АИИ-70 test unit

protect the primary winding from overvoltage. A high-voltage transformer *Tr3* rated 2 kV A, 100 V/50 kV, has one of its secondary winding terminals grounded. With the sinusoidal voltage drawn from the supply line, the crest factor of the secondary voltage in the no-load conditions does not differ from that of the sinusoidal wave by more than 5%. A resistor *R* protects the transformer and the hot-cathode rectifier tube from overload as the specimen ruptures. The test unit has a measuring cell for type testing of liquid dielectrics and a half-wave rectifier network built around a hot-cathode rectifier tube *T* to carry out d.c. breakdown tests; the circuit supplies d.c. voltage of negative polarity to the test specimen. A microammeter μA connected in the plate circuit measures leakage current, whenever necessary, with the switch *K3* held open. A spark gap *SG* that bypasses the capacitor and resistor protects the micro-

ammeter against overload. The microammeter is designed to read current in a few ranges of measurement.

The test unit has a control desk (Fig. 5.20), protective guard, and a ground hook (not shown) to drain off the charge from the test specimen and to ground the high-voltage terminal. The error in test voltage is within $\pm 2\%$. The instruments and controls arranged on the desk include a kilovoltmeter, signal lamps, a circuit breaker with built-in means for overvoltage protection, and other devices.

The test unit is designed for three types of test:

1. Short-term tests at rectified voltages up to 70 kV for not more than 10 min at 3-min intervals.
2. Long-term tests at rectified voltages for up to 8 h.
3. Short-term tests at alternating voltages up to 50 kV for not more than 1 min at 5-min intervals.

If it is necessary to carry out a d.c. breakdown test, the sequence of operations is as follows. Attach the hot-cathode rectifier tube adapter to the flap door of the control desk, set up the protective guard, switch on the unit, and connect the specimen in the circuit. Now, being sure that the voltage regulator is in the zero position, disconnect the high-voltage terminal from the ground hook and push the button to apply voltage to the control desk. With the source power turned on, the green lamp lights up; if the circuit breaker comes into action, the red lamp comes on.

Next, raising voltage with the voltage regulator, perform the test in accordance with the prescribed test procedure and take the readings on the kilovoltmeter and microammeter. After completing the test, set the voltage to zero and hang the ground hook on the high-voltage terminal. This done, the specimen is inspected and changed for a new one if necessary.

In a.c. breakdown tests, there is no need for the rectifier tube adapter. After connecting one electrode of the specimen to the transformer's high-voltage terminal and the other electrode to the grounded terminal, the test proceeds in the same manner as described above. Another test unit, type AIM-80, is designed to test insulating oils and other liquid dielectrics for dielectric strength. The laboratory unit can provide for an effective commercial-frequency

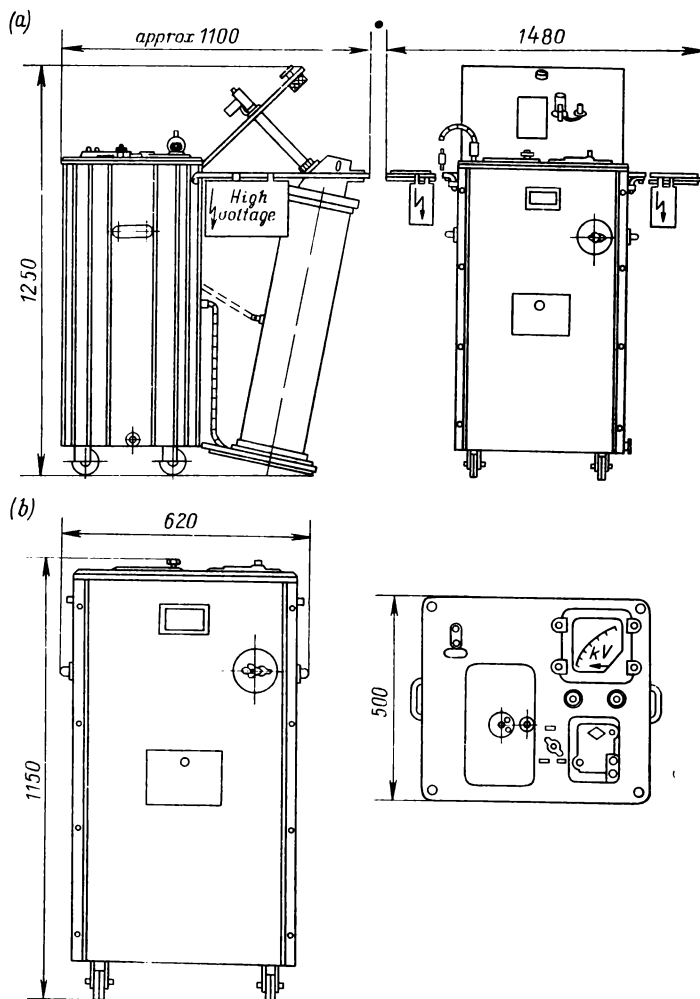


FIG. 5.20. General view (a) and control desk (b) of type AHI-70 test unit

voltage of up to 80 kV at a rated power of 0.5 kV A. The volume of the measuring vessel is 400 cm³.

Safety measures. Strict observance of safety rules is essential in running high-voltage test apparatus. The value of current that appears to be a hazard to the man's life is merely 20 mA. Every high-voltage test unit should be properly guarded to exclude accidental contact of the attendants with high-voltage terminals and leads, test specimens, measuring devices, resistors, and other elements of high-voltage circuits.

The persons receive a permit for work on high-voltage units only if they have passed a test in safety engineering. A safety briefing log must contain the following record: the kind of instruction given, the date, the family name, Christian name, patronimic, and the signature of the person who has passed the examination. The examination record sheet should be signed by the safety engineer, the instructor, and the examiner.

It is permissible to run a high-voltage unit only in the presence of two operators, one being in charge of the job. Before switching on a high-voltage source, all the doors and protective guards should be tightly closed. The unit can be connected to the power source only with the supervisor's permission.

After applying the voltage, any switch-overs in the circuit, replacement or readjustment of the specimen are inadmissible. Before replacing the specimen, the operator should disconnect the unit and thoroughly ground the transformer's high-voltage terminal and also the terminals of high-voltage capacitors if these are present in the circuit; for this the operator should cast on the terminals the hooks connected with the ground electrodes by means of flexible wire. Such a hook is fitted with an insulating handle to provide safety for the operator who grounds the test unit. After replacing the specimen or executing the necessary change-overs, the operator removes the ground hooks (rods) from the terminals.

High-voltage test units must have warning notices (such as "Care, high voltage") at the places where they catch the eye, warning lights, and also a set of insulating means such

as rubber mats, rubber gloves, and also tools with insulating handles.

The supervisor responsible for the test procedures must see to it that the laboratory staff and the apprentices who make measurements on the high-voltage test apparatus follow carefully the safety instructions.

ARC RESISTANCE

6.1. General

Electrical insulating material and insulation components used in electrical equipment can be exposed to arc, spark, or corona discharges. It is highly essential that they should stand up to the effect of these discharges for a more or less long period of time. Examples of insulation elements exposed to arcing may be arc chutes of switchgear and partitions between the neighboring break contacts of multipolar circuit breakers. Insulation elements are commonly made from the composite materials of organic and inorganic origin. Arcing brings about partial disintegration of the surface layers of a material and changes its characteristics. Thus an arc can increase the surface conductance of insulation, decrease its mass, cause partial burnout at the place where it strikes the material, and trigger other unwanted processes.

By arc resistance one usually understands the length of time that an insulating material can resist the action of an arc, retaining the desired electrical and physicochemical properties (surface resistivity, mass, chemical structure) or restoring some of its properties (surface resistivity) a short time after arc extinction.

Apart from arc discharges, the insulation in service can be exposed to spark discharges that affect its surface. Sparking causes nonuniform heating and, sometimes, erosion of the insulation surface, and may subsequently result in a serious damage or breakdown in an insulator. By definition, spark resistance is the length of time a material can resist the formation of a conductive path on its surface by spark discharges, retaining its physical and electrical properties, in particular the dielectric strength.

One should differentiate between the tests for arc resistance and those for spark resistance. The tests for spark resistance involve the action of a continuous stream of

sparks on a test specimen along its surface for a definite length of time, which do not pass into an arc. For producing a discharge typical of sparking rather than of arcing, the test circuit must have an additional resistance or reactance inserted across the secondary of a test step-up transformer.

Testing of, say, porcelain insulators for spark resistance shall last 4 min at a specified voltage of commercial frequency applied to the insulator through an air gap 25 to 40 mm in width. An arc that breaks through the air gap is an indication that the insulator has failed.

Partial, nondisruptive discharges appearing on the surface of insulation are called corona discharges. They usually occur at the places of high field strength and do not spread over the entire gap between the electrodes. These discharges also cause deterioration in the surface properties of insulation. Corona resistance is the length of time that a material can withstand the action of a corona without showing noticeable degradation of its properties.

Given definite conditions, a corona may build up near the sharp edges of electrodes: it spreads over a relatively narrow region adjacent to the electrode. The effect of the corona itself and the chemical compositions that evolve under its action bring about the disintegration of organic insulation; after some period of time, t_{cor} , breakdown can result.

The characteristics used for the comparative estimation of materials under corona conditions are an initial corona voltage U_{in} , critical corona voltage U_{cor} , and time t_{cor} . The initial voltage U_{in} is a minimum voltage conducive to the formation of a corona, either detected or observed; at this voltage the corona discharge may persist long without causing breakdown in the test specimen. The critical voltage U_{cor} is the voltage at which the corona process culminates in breakdown of the specimen in a definite time t_{cor} , under the specified test conditions. The characteristics mentioned above are quite conditional; it makes sense to consider them only in conjunction with the stipulated test conditions, the test technique chosen, the dimensions and shape of specimens and electrodes, the frequency of the applied voltage, etc. It is easy to see that

U_{cor} decreases with increased t_{cor} within definite limits. The plot of U_{cor} versus t_{cor} may serve as an illustrative example. For constructing such a curve, perform the test as follows. Apply a voltage U_1 in excess of the initial corona voltage to a specimen until it breaks down after

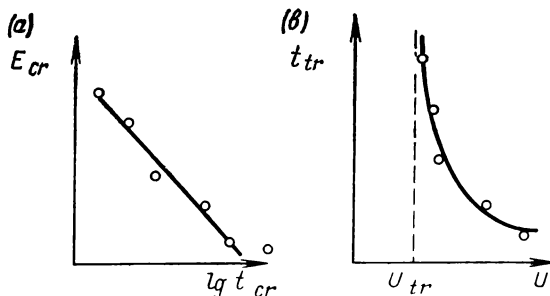


FIG. 6.1. Typical relations for corona resistance (a) and tracking resistance (b)

time period t_1 . Then make the test on a new specimen at $U_2 > U_1$ and note the time of breakdown, $t_2 < t_1$. Repeat the test several times at increased voltages. Now plot U against t . The plotted function is the life curve for the material tested under corona conditions. Plotting the corona time t_{cor} as abscissas in the log scale and the field strength as ordinates, we shall obtain the curve (rectified) as shown in Fig. 6.1a, which obeys the equation

$$E_{cor} = A - m \log t_{cor}$$

where A is the electric strength of a dielectric tested at a uniformly increasing voltage; E_{cor} is the field strength at the instant of breakdown for the corona time t_{cor} . The coefficient m is the measure of corona endurance; the faster a decrease in the field strength at which a dielectric ruptures, the lower its corona endurance.

The expression for the coefficient of corona endurance is

$$m = \frac{A - E_{cor}}{\log t_{cor}}$$

One more variety of arc resistance is tracking resistance. When organic insulation held in a contaminated humid

atmosphere is subjected to voltage, sparks (creeping discharges) appear on its surface, which move from place to place. The process arises from the following. A film of moisture that precipitates from the humid atmosphere on to the surface of insulation contaminated with dust, soot, dissolved salts and other foreign matter adds to its surface conductance. A relatively high leakage current produced by the externally applied field cannot spread uniformly over the surface; in some places the current density becomes rather high. At these places the moisture film vigorously evaporates as a result of thermal dissipation of the electric energy, so the conductive path of the film breaks up to yield a strong spark. As the spark goes out, the subsequent redistribution of the surface current density leads to a rapid evaporation of the film in another region, so that the next spark results, and so on. The impression is that the sparks emerging on the surface "run" from place to place gradually making way, as is often the case, for one of the electrodes.

This phenomenon can arise both at low voltages and high current densities and at high voltages and low leakage current densities. In the first case, it is the thermal processes that play the main role. In the second case, chemical and erosion processes are responsible for creeping. Either of the two types of creepage cause irreversible changes in the material surface layer and appearance of current-carrying low-resistance channels (tracks) on its surface, along which impermissibly large leakage currents can flow. The process of formation of conducting tracks on the surface of a solid dielectric exposed to an externally applied field is known as tracking and the ability of a dielectric to resist the formation of a conducting path for a definite length of time under the action of surface discharges is called tracking resistance, or endurance.

Test methods for determining tracking resistance have been developed and the test parameters specified to enable a comparative estimate of this characteristic. These parameters are conditional and require consideration only in conjunction with the test methods employed.

One of the most widespread parameters is a tracking voltage U_{tr} determined as follows. Place on a flat specimen

two electrodes at a certain distance from each other and introduce drop by drop a salt solution of the prescribed composition into the interelectrode gap. Now raise the voltage in a step-by-step manner and note the current with each increment of the test voltage after letting 50 drops fall into the gap. The test voltage at which the current reaches the preset value of I_{tr} as a result of tracks formed on the surface that short out the electrodes is the value of tracking voltage U_{tr} . Thus, U_{tr} is a minimum voltage responsible for the formation of short-circuiting tracks between the electrodes and appearance of the current I_{tr} of the specified value. The voltage U_{tr} may serve as a characteristic of the material only under the definite test conditions. Another method of test involves measuring the time (proportional to the number of steadily falling drops) during which the current reaches the preset value with each increase in test voltage. The step-by-step increase in voltage U (across a new specimen at every step of voltage rise) causes a decrease in the time t or, which is the same, in the number of drops, required for the current to reach the preset value. Erecting now an asymptote to the curve $t(U)$, we can find U_{tr} at the point of its intersection with the X -axis (Fig. 6.1b).

The comparison studies on the tracking resistance of various materials enable us to conclude that the quantity U_{tr} can serve for the comparative estimation of the tracking resistance of materials only if they operate at low voltages. For the estimation of the tracking resistance of materials destined for work at high voltages, another test method has been suggested. By this method, a tubular specimen fitted out with electrodes at its ends is placed in a temperature-controlled humidity chamber and subjected to a high voltage of the preset value. The temperature in the chamber is changed according to the prescribed schedule and the time t_{tr} required for the formation of tracks is noted. The time t_{tr} and the other parameters measured allow us to judge how the material stands up to tracking at high voltages.

Arc resistance is determined by exposing the surface layers of a specimen to an electric arc, noting the qualitative changes in the material and the time of the arc action,

Tests are conducted in such a manner as to cut down the time of testing to a minimum.

Materials are tested for arc resistance at a.c. voltages above 1 000 V and at d.c. voltages up to 1 000 V. The choice of the type of testing depends on the specific features of a material or product, the function it must serve, and its service conditions. The test facilities and methods for determining the parameters of arc resistance are prescribed in pertinent standards, which also specify the test conditions and measuring procedures.

6.2. A. C. Arc Resistance

Materials are exposed to an arc produced by a low current of high voltage at commercial frequency. The arc drawn between two electrodes resting on the surface of a test specimen causes the formation of a conducting bridge between the electrodes. Since the resistance of the bridge is lower than that of the air gap between the electrodes, the bridge shunts the air gap and the arc goes out. The instant of arc extinction is thus the moment at which the conducting path has formed between the electrodes. The parameters of arc resistance here are the arc current I_a and time t_a required to reach failure.

The specimens used for arc resistance testing are flat test pieces of any shape, not less than 3 mm thick. The area of a specimen shall be sufficient to arrange the electrode tips at least 8 mm away from the specimen edges. If a few tests are run on the same specimen, the distance between the testing zones shall be at least 15 mm. The surface of a specimen shall be clean since dust, moisture, and finger prints may alter the test results. Dents, cracks, burrs, and scratches visible with the naked eye on the surface are impermissible.

The type of mechanical treatment chosen for the preparation of a specimen must not change the material properties. Specimens are subject to preconditioning and conditioning before test in accordance with instructions and test specifications. If these do not prescribe the procedure of conditioning, the specimens shall be conditioned for 24 h at about 20% relative humidity at $55^{\circ}\text{C} \pm 2^{\circ}\text{C}$.

For each grade of material, 10 tests are run on at least 3 specimens at 45 to 75% relative humidity at 15 to 35°C.

The electrodes used in testing are rods 2.5 ± 0.1 mm in diameter, made from tungsten with an addition of toria.

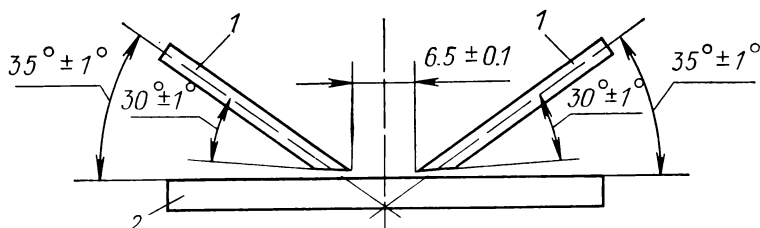


FIG. 6.2. Location of electrodes with respect to specimen

They have pointed ends cut flat at an angle of 30° to the rod axis and ground with emery paper to remove burrs and other irregularities. As seen from Fig. 6.2, electrodes 1 set in

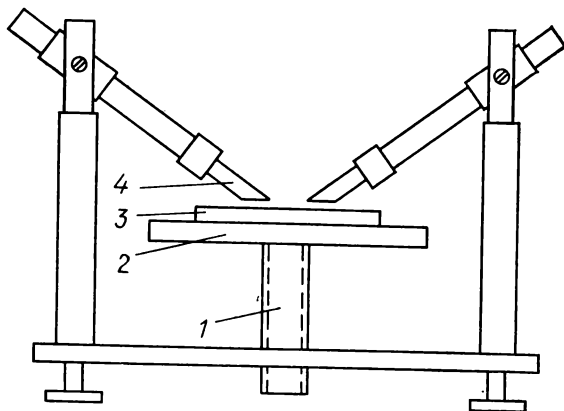


FIG. 6.3. Electrode holder with specimen support

the same vertical plane, rest on the surface of a specimen 2 at 35° to its plane. The angle formed between the electrode axes is 110° and the distance between the electrode tips is 6.5 ± 0.1 mm.

A test unit consists of an electrode holder, specimen support, and a power source. The electrode holder (Fig. 6.3) allows for setting electrodes 4 to a desired angle and moving each along its axis. The support 2 for a specimen 3 can

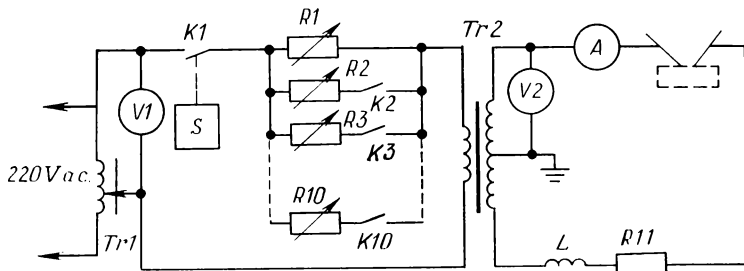


FIG. 6.4. Circuit diagram of a.c. high-voltage source

move vertically by turning a micrometer screw 1. Adjusting the vertical position of the specimen enables controlling the force with which the electrodes bear against the specimen. According to the standard, this force shall be equal to (0.5 ± 0.05) N. The specimen shall not deform under the applied force.

The source of high voltage (Fig. 6.4) strikes an electric arc at a voltage of 12.5 kV and a current of 10 to 100 mA between the electrodes. The voltage is drawn from the secondary of a transformer *Tr2*, whose center tap is grounded. It is also possible to use transformers with an ungrounded center tap, but then one of the electrodes must be grounded. The voltage across electrodes is measured with an electrostatic voltmeter *V2*, and the arc current with an ammeter *A*. The error in the measurement of voltage and current shall not be in excess of 2%. The voltage and current derived from the secondary of *Tr2* is controlled with an autotransformer *Tr1* and resistors *R1* through *R10*. A special switch *S* connects the resistors in the circuit in a definite sequence to obtain the desired arc current (Table 6.1) at an invariable voltage.

Arcing generates high-frequency oscillations which interfere with the operation of radio receivers. A filter consisting of a resistor *R11* and an inductor *L* serves here as

TABLE 6.1

Test Procedure for an A. C. Arc Resistance Measuring Unit

Current set- ting number	Arc cur- rent, mA	Condition of arcing	Current set- ting number	Arc cur- rent, mA	Condition of arcing
1		Intermit- tent	7	40	Continuous
2	10		8	50	
3			9	60	
4	10		10	70	
5	20	Continuous	11	80	
6	30		12	90	
			13	100	

an RFI suppressor. Also, to reduce radio noise, the source power of the entire set shall be at least 10 times the power drawn by the set. The time of arcing is measured with a time meter built in the set or, if this is not available, with a stopwatch.

The field where arcing takes place shall be enclosed with a transparent shield to provide safety for the operator and protect the arc from drafts that can cause its deflection. An air exhauster should be provided to remove the products of burning.

Before starting with the tests, the set is prepared for proper operation. For this the operator switches on the supply source to energize the set with the electrodes disconnected, closes a contact *K1*, adjusts *Tr1* to set the voltage in the open secondary circuit of *Tr2* at 12.5 kV that can be read on the voltmeter *V1*, and then disconnects the set. Next the operator lets the electrodes rest on a special ceramic support and again connects the set to the supply. With the contact *K1* being closed, the operator connects a resistor *R1* in the circuit to set the arc current at 10 mA and then closes a contact *K2* to cut in a resistor *R2* and thus adjust the arc current to 20 mA. In a similar manner, he connects resistors *R3* through *R10* in the circuit and checks for the current settings in steps, and then disconnects the unit from the supply. In this preparatory operation the voltage is kept invariable.

The test is run as follows. The operator places a test specimen on the support and swings the electrodes down to make them rest on the specimen surface. He now applies voltage to the set and turns on the switch *S* and the contact control system. Connecting in turn the resistors, the operator varies the condition of arcing in steps, keeping the arc glowing at every current setting for 60 s. The first three settings of current produce intermittent arcing. The arc goes on for 0.25 s at intervals from 1.75 s at the first setting to 0.25 s at the third setting. Starting from the fourth step the condition of arcing becomes continuous, and the arc current rises 10 mA with each step.

The operator stops testing as soon as the conducting path forms between the electrodes. Indicative of the bridge formation is a characteristic glimmer of the specimen surface between the electrodes. This glimmer may appear as a faintly luminous streak or a number of sparkles. Apart from arc extinction, the readings on the milliammeter can also point to the appearance of the conducting path. If the material melts or burns under the action of arcs, the testing should be discontinued.

The result of an individual test is the total time in seconds elapsed from the start of testing to the instant of bridge formation. The final result that determines the resistance of the material to a.c. arcs is taken to be both the arithmetic mean of the test results and the least measured value of time required to produce a conducting path. For materials which melt or catch fire rather than develop a conducting path on exposure to arcs, the measure of arc resistance is the depth of melting or erosion and the time period from the start to the end of testing.

6.3. D.C. Arc Resistance

It is customary to evaluate the d.c. arc resistance of materials in a qualitative manner. In tests, a specimen is exposed to an arc of direct current at 220 V. The arc tends to form conducting paths which remain or disappear after specimen cooling; some materials melt, char, burst, and burn. The tests determine the class of arc resistance of

a material. The material may fall into one of the six classes depending on the effects produced by the arc.

The test specimens are in the form of a square plate or disc 12 mm in thickness. The diameter of the disc or the side of the square shall be not less than 80 mm. If the material under test has a smaller thickness, it is permissible to place several specimens in a dense stack to attain the desired thickness. For anisotropic materials, technical

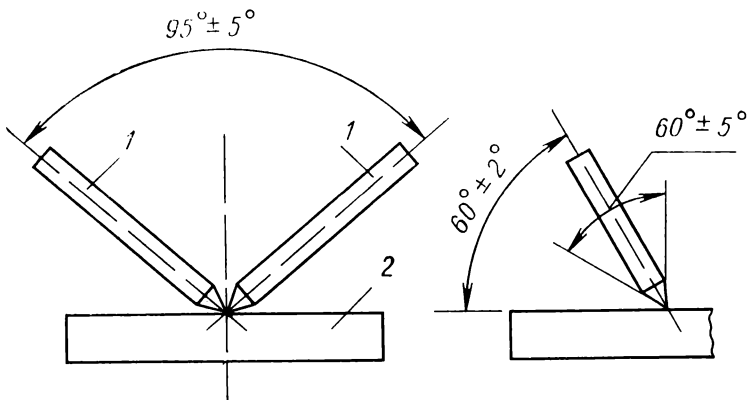


FIG. 6.5. Location of electrodes relative to specimen

instructions and test specifications must prescribe how to orient the specimen with respect to the plane of electrode axes and also suggest the method of mechanical treatment of each material.

Test specimens shall be clean in the zone of arcing and free from cracks, dents, hollows, and other defects.

Specimens are preconditioned and conditioned according to instructions and test specifications. If these do not mention the particulars, the specimens are conditioned in the air at less than 20% relative humidity at $(55 \pm 2)^\circ\text{C}$ for 24 h. Tests are made on ten specimens in the air under normal conditions of 45% to 75% relative humidity and 15°C to 35°C .

An electric arc is drawn between two round copper-uncoated carbon welding rods 8 mm in diameter. The electrode tips are made pointed to a cone with an angle at the apex

of 60° (Fig. 6.5), the apex being filed to a radius of 0.4 to 0.6 mm. Electrodes 1 are placed symmetrically in the same plane at 60° to the surface of a specimen 2. The angle formed between the axes of electrodes shall be equal to 95° . Each of the electrodes shall bear against the specimen at

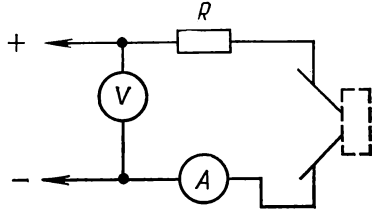


FIG. 6.6. Circuit of connection of electrodes

a force of 0.1 to 1 N, but not cause its deformation. Before commencing another set of tests, the electrodes must be cleaned and pointed if necessary.

The test set has an electrode holder furnished with a synchronous motor to draw apart the electrodes along the specimen surface at a steady rate of 1 mm/s. The inter-electrode gap is read on the scale of an instrument.

The set must be provided with an air exhauster for removal of gaseous products.

Any d.c. source that supplies a voltage of 220 V is suitable for initiating an arc if the ripple amplitude of the alternating component does not exceed 5%. As seen in Fig. 6.6, the circuit for producing an arc includes a voltmeter V and ammeter A to control the arc voltage and current, and also a resistor R to limit the arc current. The error in voltage shall be within 2%. Standards do not specify the error in current, so that any detector may suffice in place of the milliammeter.

A test specimen is placed in the horizontal plane, with its flat surface facing the electrodes. At the initial moment the electrodes must be in contact with each other and bear against the specimen. On applying the voltage, the motor-driven electrode holder draws the electrodes apart, between which an arc appears. The operator disconnects the power source as the interelectrode gap reaches 20 mm, or even earlier if the arc goes out.

The criteria of placing materials into classes (class L1 through L6) are given in Table 6.2.

TABLE 6.2

Arc Resistance Classes (at up to 1 000 V d.c.)

Class	Arcing at interelec- trode distance up to 20 mm	Conducting path in test spe- cimen		Effect of arcing on material
		in arcing	after speci- men cooling	
L1	Continues	Appears	Remains	Charring, burning
L2	Ceases	Appears	Disappears	Bursting
L3	Continues	Appears	Disappears	Destruction absent
L4	Ceases	Does not appear	—	Melting, fuming
L5	Continues	Does not appear	—	Destruction absent
L6	Ceases	Does not appear	—	Destruction absent

ELECTRICAL TESTING UNDER VARIOUS ENVIRONMENTAL CONDITIONS

7.1. General

The properties of electrical insulating materials heavily depend on temperature, humidity, sunlight, pressure, and other external influences. In various geographical areas of the globe, which greatly differ in climate, insulation must often operate under the conditions at which a diversity of external factors simultaneously affect its properties. Thus in tropical humid regions a high ambient temperature combined with increased humidity, intensive solar radiation, and enhanced microbiological activity present a most severe hazard to the life of insulation. In cold climate regions, insulation has to withstand exposure to low temperature and high humidity (frost, glaze). The operating conditions of insulation are very specific in high-mountain areas where a lowered atmospheric pressure and sharp daily variations in humidity and temperature have a pronounced effect on the insulation properties. The standard on a material or component specifies the conditions of testing in accordance with its service conditions. Long-term holding at high temperatures is also necessary in conducting accelerated aging tests.

The most typical test conditions for determining the electrical characteristics of materials are the following:

1. Normal conditions (65 % relative humidity at 20°C and atmospheric pressure of 760 mm Hg \approx 101.3 kPa). These conditions of test are advisable for materials whose technical instructions do not specify any other particular requirements.
2. Conditions of the highest humidity ($95 \pm 2\%$ relative humidity) at room temperature, $20^\circ\text{C} \pm 2^\circ\text{C}$.
3. Conditions of the highest humidity ($95 \pm 2\%$ relative humidity) at increased temperature, $40^\circ\text{C} \pm 2^\circ\text{C}$.

4. Dry atmosphere (relative humidity below 1.5%) at room temperature.

5. Dry atmosphere (less than 20% relative humidity) at enhanced temperature, from 50 to 1 000°C.

6. Cold atmosphere, at minus 10 to minus 65°C.

There are special test units capable of securing the desired environmental conditions such as temperature, humidity, and pressure at which it is necessary to measure certain electrical characteristics of specimens. Humidity cabinets (hygrostats) secure the preset humidity. For this purpose, a pan filled with a solution of calcium chloride or sulfuric acid is put on the bottom of the hygrostat chamber; the solution concentration must be such as to provide the desired humidity at the given temperature. Using substances such as P_2O_5 and anhydrous $CaCl_2$, which readily absorb moisture, it is possible to keep the humidity in a desiccator or hygrostat close to zero. The period of holding specimens under the specified conditions prior to test may be from 1 to 16 h. Specimens are weighed to check them for moisture content. A specimen is considered absolutely dry if its mass does not decrease on subsequent drying.

7.2. Testing at High and Low Temperatures

The test units designed to determine the electrical characteristics of specimens at high temperatures are constant-temperature cabinets provided with electric, water, or other types of heater. Thermally insulated double walls of the test chamber can keep the air temperature invariable for a long period of time. The temperature is measured with thermometers or thermocouples. Since the temperature cannot be absolutely identical in the entire volume of the chamber, the tip of a thermometer or the hot junction of a thermocouple should be placed as close to the test specimen as possible. In an empty chamber the temperature levels off in a manner other than in a chamber loaded with specimens. For better temperature distribution over the entire volume of the chamber, the heater elements are arranged not only at the bottom and in the walls but also in the chamber door, and the air is intensively mixed with a fan (Fig. 7.1). The

heater elements used here are wound wire from nichrome or any other alloy of high resistivity. Hermetically sealed tubular electric heaters are noted for a long service life.

In running electrical tests, open electric heater elements must be thoroughly protected with grounded shields against

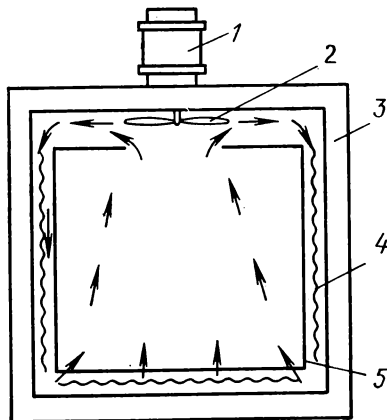


FIG. 7.1. Constant-temperature chamber

1—electric motor; 2—fan; 3—thermal insulation; 4—heater elements; 5—inner perforated casing

a breakdown discharge on an element or its contact with a high-voltage lead.

A temperature control device can automatically switch off part of heater elements (commonly one third of the total, evenly distributed over the chamber) when the temperature reaches the upper limit, or switch on the elements when the temperature drops to the lower limit.

There are several methods for measuring temperature.

Mercury-in-glass thermometers. They are used for measuring temperatures in the range from -35 to $+350^{\circ}\text{C}$. The upper temperature limit can be raised to $+660^{\circ}\text{C}$ by filling the free part of the capillary tube with nitrogen or any other inert gas under pressure to guard against mercury evaporation. Liquid-filled low-reading thermometers are used for measuring low temperatures, down to minus 190°C .

Glass thermometers show a relatively high heat capacity and large thermal lag, and therefore they should be employed for the measurement of steady temperatures, where the dissipation of thermal energy is rather high, for example, inside the cores of tubular enamelled resistors.

The permissible error of industrial and laboratory thermometers with a scale division of 0.1°C or 0.2°C ranges from $\pm 0.2^{\circ}\text{C}$ to $\pm 1^{\circ}\text{C}$.

A shortcoming of the mercury thermometer is its fairly large thermal lag, which makes this temperature meter inadequate for the measurement of sharply varying temperatures. Thermocouples and resistance thermometers serve well under these conditions.

Thermocouples. These are the most widespread meters of temperature. The thermal emf at the terminals of a thermocouple is directly proportional to the difference in temperature between the hot and the cold junction and depends on the metals and alloys employed. The first four thermocouples given in Table 7.1 belong to the standard types

TABLE 7.1

Properties of Thermocouples

Thermocouple	Thermal emf per degree of temperature difference, $\text{V}/^{\circ}\text{C}$	Maximum permis- sible temperature at hot junction, $^{\circ}\text{C}$	
		long-term	short-term
Chromel <i>vs.</i> copel	69	600	800
Chromel <i>vs.</i> alumel	41	1 100	1 250
Platinum-rhodium <i>vs.</i> platinum	10	1 400	1 600
Iron <i>vs.</i> constantan	50	600	800
Manganin <i>vs.</i> constantan	50	200	—
Nichrome <i>vs.</i> constantan	57	600	—

(Soviet State standard 3044-77). A platinum-rhodium *vs.* platinum couple (the platinum-rhodium alloy consists of 90% Pt and 10% Rh) features chemical stability to the attack by an oxidizing medium; a reducing medium has a destructive effect on platinum. Other alloys have the

following approximate compositions: chromel consists of 90% Ni and 10% Cr; alumel, 1% Si, 2% Al, 43.5% Fe, 2% Mn, the balance Ni; copel, 43% Ni + Co, 1% Mn, the balance Cu. Most popular for the measurement of temperatures up to 600°C is the type TXK chromel-copel couple which shows high thermal emf and small thermal lag. A chromel-alumel couple, type TXA, is most adaptable to the measurement of high temperatures, up to 1100°C. This thermocouple is comparatively cheap, reliable in service and simple to handle. Constantan-base thermocouples are rather practicable and comparatively cheap. Apart from the thermocouples listed in the Table, other types are available.

The extension leads for base-metal thermocouples are made from the same metals as the couple itself; for noble metal couples, the extension leads are prepared from cheaper metals and alloys, which, however, must satisfy the requirement for thermal compatibility. This means that within the possible range of temperatures at the thermocouple free ends, the extension leads should exhibit the same thermal emf *versus* temperature difference relation as the couple itself. Where this condition is observed, the leads will not affect the results of temperature measurements.

In taking temperature measurements with a thermocouple, it is necessary to make a correction for the temperature at its free ends, since this temperature usually differs from that at which the thermocouple was calibrated. If a thermocouple was calibrated at T_0 of its free ends, while in service the temperature at its free ends is T'_0 , then we must add a correction to the reading taken from the scale equal to $(T'_0 - T_0) K$, where K is a coefficient dependent on the temperature being measured. So that this correction will be constant, it is well to stabilize the temperature at free ends by placing them, say, in a thermally insulated massive box or a constant-temperature chamber. There are devices which automatically apply a correction for the difference in temperature at free ends.

Commercially available thermocouples operate with millivoltmeters of accuracy classes 1 and 1.5. The scale of these millivoltmeters, for example, the M64 type, is calibrated to read the temperature directly in degrees Celsius. A compensation method provides for ease of thermal emf measure-

ment with the aid of portable potentiometers capable of detecting low emf's, up to 100 mV, the measurement error being kept within ± 0.1 mV. KСП-2, KСП-3, and KСП-4 potentiometers of accuracy class 0.5 may serve as some of the examples. The ПП-63 potentiometer of accuracy class 0.05 is even more accurate. This device is often used for checking other automatic potentiometers and millivoltmeters.

Thermocouples are calibrated and adjusted against a standard thermocouple or thermometer. The thermocouple or thermometer being checked against the standard is immersed in a bath with a liquid, the temperature of which is then slowly increased. The liquids used in this test are a mineral oil (up to 200°C) and molten salts (200 to 600°C). Checks at higher temperatures are made in laboratory ovens.

Resistance thermometer. This temperature meter utilizes the effect of variation of metal resistance with temperature.

Platinum and copper are most common metals used for these thermometers. The choice of the metal depends on its chemical stability against the given medium at increased temperatures. Copper makes a suitable material for the measurement of temperatures within the range from minus 50 to plus 180°C in a dry atmosphere free from aggressive gases. Platinum resistance thermometers can measure temperatures from minus 200 to plus 650°C in oxidizing and inert atmospheres. Copper resistance thermometers are made from fine wire of round cross section wound on a plastic arbor and insulated with thin-layer and heat-resistant insulation (enamel or silk). Platinum wire is wound into a winding on a support from mica plates without using any insulation. The resistance of a winding is set at 50-100 Ω . The winding is enclosed in a sleeve (and sealed sometimes) to protect it from exposure to external influences such as moisture and aggressive gases. In operation, a resistance thermometer is connected into a resistance measuring circuit, mostly into an unbalanced or balanced bridge; the latter type can have a moving-coil ratiometer to measure the temperature.

Semiconductor temperature-sensitive resistors have a large temperature coefficient of resistance, ranging from minus 0.02 to minus 0.06 K⁻¹, and a high initial resistance, in the order of 150 k Ω . Some of these resistors are prepared from the

sintered mixtures of oxides: (a) copper and manganese (an example being the MMT type produced on a commercial scale); (b) cobalt and manganese (KMT type). Other oxides are also suitable for use along with sulfides, selenides, and tellurides. These resistors exhibit a higher response and lower thermal lag than wire resistors. Extension leads

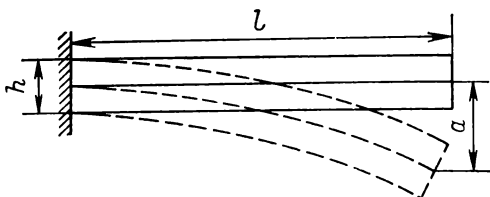


FIG. 7.2. Deformation of a bimetallic strip on heating

have no effect on the measurement results here too. However, the reproducibility of characteristics of temperature-sensitive resistors greatly depends on the production technique employed and the presence of impurities.

In long-term tests, it is often required to keep the temperature steady at the desired level. Automatic temperature controllers used for this purpose come in a variety of designs.

Bimetallic temperature controller. This device contains a bimetallic strip obtained by hot rolling and pressing together two strips, the metals of which differ in the temperature coefficient of length. The bimetallic strip contracts or expands as the ambient temperature changes, and thus bends up and down, either closing or opening the contacts of a temperature control device.

For a bimetallic strip clamped at one of its ends (Fig. 7.2), the sag of its free end as the temperature changes from T_0 to T can be expressed in approximate form by the formula

$$a = \frac{3}{4} \frac{(T - T_0) (\alpha_2 - \alpha_1) l^2}{h} \quad (7.1)$$

where α_1 and α_2 are the temperature coefficients of length for the two metals respectively.

The linear dimensions l and h that enter this equation must be expressed in the same units of measurement. The

equation holds for the strip whose layers are equal in thickness.

The sensitivity of a temperature controller can be increased by making its bimetallic strip of two metals or

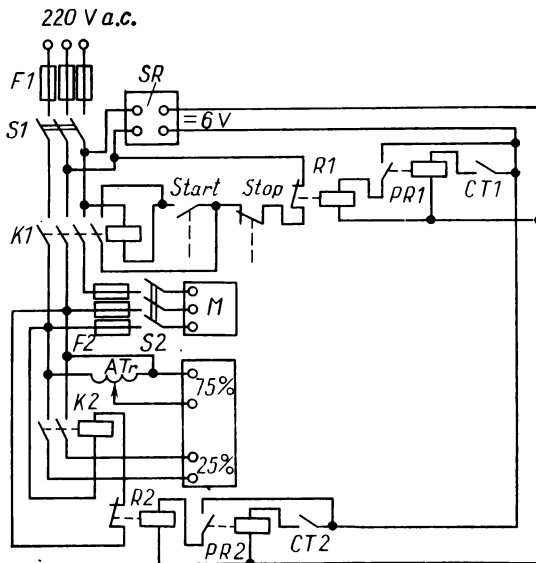


FIG 7.3. Automatic temperature control circuit diagram

CT1 and *CT2*—contact thermometers; *R1* and *R2*—relays; *PR1* and *PR2*—polarized relays; *K1*—main contactor; *K2*—winding temperature control contactor; *M*—electric motor; *SR*—selenium rectifier; *At*—autotransformer; *F1* and *F2*—fuses; *S1*—main switch; *S2*—fan motor switch; 75% and 25% correspond to the power of heater elements

alloys (such as copper and invar) which greatly differ in the temperature coefficient of length; for copper $\alpha = 15 \times 10^{-6} \text{ K}^{-1}$ and for invar, $\alpha = 10^{-6} \text{ K}^{-1}$.

Contact thermometer. This temperature controller uses a mercury thermometer with contact leads soldered into its capillary tube. As the temperature rises or falls, mercury in the tube makes or breaks the corresponding contacts. Fig. 7.3. shows an example of the automatic temperature control circuit based on contact thermometers. Here *CT1* is the main thermometer while *CT2* disconnects all heater elements and also the electric motor of a fan if for some

reason or other the temperature rises 5°C above the preset value.

The Soviet industry also turns out electronic temperature controllers of various designs.

In measuring the electrical characteristics of a specimen in a constant-temperature chamber, the bushing insulators inserted through its wall should have a high insulation level since a rise in temperature decreases the resistance of insulation. It is preferable to use quartz-glass or radio-ceramic bushings and arrange them so as to ensure their proper cooling.

Cryostats are double-walled chambers provided with thermal insulation between the two walls to keep low temperatures at a desired level. A small-volume Dewar flask—a glass flask with double silver-coated walls—can do as a cryostat; the air in the interspace between the walls is evacuated to provide for thermal insulation.

Low temperatures are attained using cooling mixtures. Thus ice or snow gives 0°C , a mixture of five parts of ice and one part of NaCl offers minus 21°C , and a mixture of one part ice with one part $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, minus 40°C . Solid carbon dioxide ("dry ice") has a sublimation temperature of minus 78.5°C . Liquid air, nitrogen, and helium secure yet lower temperatures. The use of liquid oxygen is unadvisable as its handling involves the danger of fire and explosion. Liquid oxygen presents a particular hazard if it comes in contact with petroleum oils.

Some cryostats use a closed circulating system where heavily compressed freon, CF_2Cl_2 , quickly expands in one section of the system and thus cools the chamber.

Combined types of test apparatus are also available, which can operate as thermostats and cryostats.

Whenever there is a need to determine the properties of a material at a definite temperature, the specimen must first be held in the chamber for a sufficiently long time to allow its entire volume to attain the desired temperature. The larger the specimen and the lower its thermal conductivity, the longer the time of holding.

It is customary to evaluate the electrical characteristics of a material by two methods. In the first method, the desired parameter is measured during heating of a specimen in

a thermostat or its cooling in a cryostat. In the second method, the specimen is held in a thermostat or cryostat and its parameters are then measured under normal conditions before and after holding. This makes it possible to estimate the effect the high or low temperatures have had on the specimen. Standards or specifications usually prescribe the test procedures and the quantities to be measured. General methods are adopted for evaluating the thermal endurance of insulating materials and insulation pieces employed in electrical equipment.

7.3. Testing at Increased Humidity

Special test units, called hygrostats, or constant-humidity cabinets, provide for the required level of humidity. Desiccators—glass flasks with ground stoppers—find common use for testing small specimens.

The content of water vapors in the air can be estimated using a few quantities.

1. The absolute humidity m , which gives the total mass of water vapors present in a unit volume of air, commonly expressed in grams per cubic meter (g/m^3).

2. The pressure p of water vapors present in the air, expressed in pascals, millibars, mm Hg, kgf/cm^2 (1 millibar = 100 Pa; 1 mm Hg = 133.3 Pa; 1 kgf/cm^2 = 9.8×10^4 Pa).

3. The relative humidity of air, expressed in percent. As is known, at a certain temperature and pressure, the air cannot contain more than a definite amount of water vapors, m_s , which saturate the given volume. The quantity m_s is the absolute humidity of air in saturation at a definite pressure p_s of water vapors. If the temperature and pressure vary in such a manner that the absolute humidity m becomes higher than m_s typical for the new conditions, the excess of moisture, $m - m_s$, precipitates as dew.

The relative humidity of air is the ratio of its absolute humidity to the absolute humidity in saturation (at the same temperature and pressure) or, which is the same, the ratio of the water vapor pressure p to the pressure p_s in

saturation (at the same temperature and pressure):

$$\varphi = m/m_s = p/p_s \quad (7.2)$$

In Soviet practice, 65% relative humidity is taken as normal air humidity. This is a reference parameter used in conducting various tests, determining the hygroscopic properties of materials in the standard conditions of moistening, etc. The content of water vapours in the air of normal humidity at 20°C is equal to $17.3 \text{ g/m}^3 \cdot 0.65 = 11.25 \text{ g/m}^3$; the water vapor pressure at normal humidity is $17.54 \text{ mm Hg} \times 0.65 = 11.4 \text{ mm Hg} = 1.52 \text{ kPa}$.

Substances such as phosphoric anhydride, P_2O_5 , dry calcium chloride, CaCl_2 , silica gel, alumina gel, and others that easily absorb moisture can reduce the relative humidity in the hygrostat chamber to zero.

The relative humidity in the chamber of a hygrostat can be varied in the range from 50 to 100% by placing on its bottom a pan filled with a calcium chloride or sulfuric acid solution of definite concentration.

For creating the atmosphere of required humidity, it often proves convenient to use saturated aqueous solutions of various substances, thereby doing away with the need for determining the density of solutions.

Given below is the relative air humidity maintained in a hygrostat at plus 20°C with the aid of saturated aqueous solutions of the following substances:

Sodium bromate, NaBr_2O_3	92
Sodium carbonate, Na_2CO_3	91
Ammonium chloride, NH_4Cl	79.2
Sodium chlorate, NaClO_3	75
Sodium nitrite, NaNO_2	65
Magnesium acetate, $\text{Mg}(\text{C}_2\text{H}_3\text{O}_2)_2$	65
Sodium bromide, NaBr	58
Calcium nitrite, $\text{Ca}(\text{NO}_2)_2$	55
Sodium biphosphate, NaH_2PO_4	52
Potassium nitrite, KNO_2	45
Potassium carbonate, K_2CO_3	44
Chromic anhydride, CrO_3	35
Calcium chloride, CaCl_2	32.3
Potassium acetate, $\text{KC}_2\text{H}_3\text{O}_2$	20
Lithium chloride, LiCl	15

Figure 7.4 shows a laboratory hygrostat with polystyrene or polytetrafluoroethylene bushing insulators for leads connected to meters which measure the electrical parameters of a specimen inside the chamber.

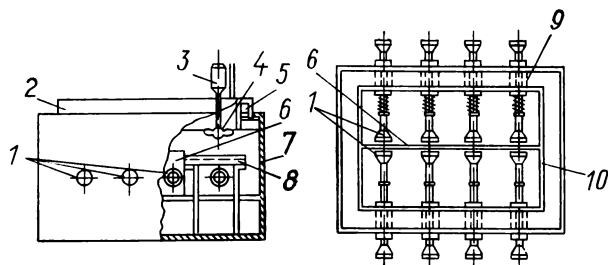


FIG. 7.4. Laboratory constant-humidity chamber

1—electrodes; 2—cover; 3—electric motor; 4—fan; 5—lock; 6—specimen; 7—chamber casing; 8—pan with solution; 9—bushing insulators; 10—specimen holder

As noted above, for the humidity to be kept constant, one should maintain a definite temperature of air in the test chamber. An automatic temperature controller is best suited for the purpose. Direct automatic control over the humidity is also a good solution to the problem. To maintain the humidity of air at 95 to 98%, the temperature of water should be slightly below (0.5°C , for example) the temperature of air in the test chamber; water in the hygrostat can be cooled by passing tap water through a copper coil placed in its chamber. A 100% humidity in the chamber is objectionable because this entails condensation of water on specimens and on the chamber cover from which it can also fall on the specimens.

A hygrostat designed to produce not only an increased humidity but also an increased temperature of air in the chamber is called a thermal humidity cabinet, in which the atmosphere approaches that typical for the tropic climate. This type of humidity cabinet can raise the temperature of air in the chamber to 80°C at about 100% humidity. The chamber draws a minimum of 12 kW. The type ВЭИ-300 thermal humidity cabinet has a working volume of 300 l and measures $950 \times 1\,050 \times 1\,850$ mm. The overall di-

mensions of the БЭИ-500 humidity cabinet of 500-l volume are $1\ 050 \times 1\ 200 \times 1\ 850$ mm. The test chamber has the shape of a cube (Fig. 7.5). The test chamber casing 1 has double walls of stainless steel provided with thermal insula-

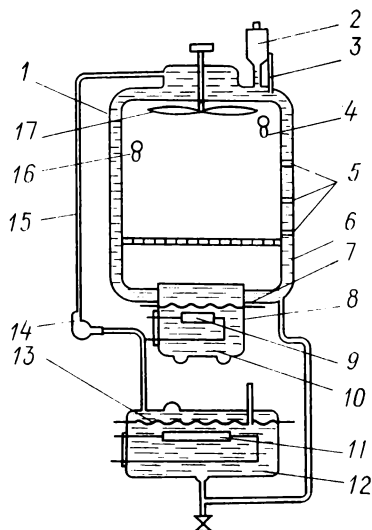


FIG. 7.5. Thermal humidity cabinet

tion. The double walls form a water jacket 6 where water heated to the desired temperature is circulating. At the bottom of the chamber there is an evaporator (humidifier) 10 with an open water surface to create the required humidity. The chamber is furnished with a dry-bulb thermometer 16 and a wet-bulb thermometer 4 to control the air humidity. The dry-bulb thermometer is at the same time the sensor of an air temperature controller, and the wet-bulb thermometer is the sensor of the controller of water temperature in the evaporator. A closed pipe system connects the chamber jacket to a water-heating tank 12 complete with a tubular electric heater 11 which raises the temperature of water to the required value. The sensor 4 is mounted inside the chamber a certain distance away from the walls. The temperature controller maintains the humidity of air in the chamber

at a preset value. A centrifugal pump 14 forces hot water from the tank along a pipe 15 into the upper portion of the jacket. The water gives off heat into the chamber and returns into the tank by gravity.

Water in the system circulates continuously. The constant humidity of air in the chamber is effected through control of the water temperature in the heating tank-water jacket system; the automatic temperature control circuit suitably connected with the air temperature sensor 16 switches on and off an electric heater 9 whenever necessary.

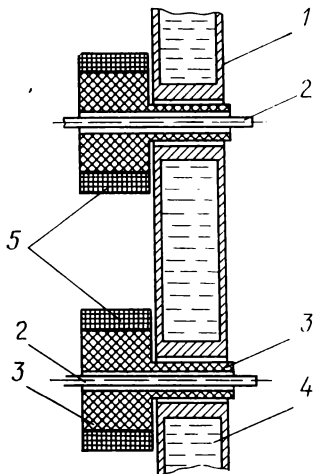


FIG. 7.6. Bushing arrangement with local heating

An evaporator tank 8 made from stainless steel and located in the bottom part of the chamber always remains filled with water to a certain level. The evaporator has a cooling coil 7 that removes excess heat and thus, together with the heater 9, maintains the water temperature in the evaporator at the desired level. The automatic control system connects the heater 9 with the psychrometric temperature sensor 4. Electronic temperature controllers using temperature-

sensitive resistors as sensors of water and air temperature ensure the most accurate adjustment and control of the temperature and humidity in the chamber.

Contact thermometers having a scale with a division not over 1°C also give satisfactory results if the thermal insulation on the outside of the chamber is good and the adjustment of the entire test unit is adequate. A fan 17 in the chamber provides for continuous and intensive mixing of the air. The fan blades rotate at a speed of 50 to 70 rpm. The chamber has a wet-bulb and a dry-bulb reference thermometer with a scale division of 0.1°C .

The chamber walls are provided with through holes to receive bushing insulators for meter leads and thermometers.

A local heating arrangement with heaters 5 and a water jacket 4 (Fig. 7.6) secures high electrical resistance of bushing insulators 3 on the inside of the chamber. As mentioned earlier, these insulators can be prepared from polystyrene, polytetrafluoroethylene, or any other moisture-resistant plastic. The local heater 5 must generate enough thermal energy so that the surface temperature of insulators should be 3°C or 4°C above the air temperature in the chamber. The temperature difference excludes the condensation of moisture on the insulator surface and thus ensures high resistance between meter leads 2.

In the door of the chamber or in any of its walls there is a peephole closed with a double glass shield and two holes provided with special doors for placing specimens inside the chamber. These doors should incorporate interlock means to remove the voltage from test electrodes when at least one of the doors is opened. Each hole features an elastic rubber sleeve that effectively prevents the outside air from getting into the chamber.

Humidity instruments. These are commonly wet-and-dry-bulb psychrometers consisting of two thermometers located adjacent to each other. The mercury-in-glass bulb of one thermometer is wrapped in a cambric rag and immersed in a flask with water. Since the water evaporates from the cambric the wet-bulb thermometer indicates a lower temperature than the dry-bulb thermometer that reads the true temperature of the air. The drier the air, the larger the difference between the readings of the two thermometers. Using the readings of the thermometers, we can determine the relative humidity of air in a chamber with the aid of psychrometric Table 7.2.

It is also possible to construct psychrometers from resistance thermometers, which can be adapted for automatic humidity control.

Another type of humidity instrument is a hair hygrometer. Consider one of the many designs of this type of hygrometer. The sensitive element here that responds to changes in humidity is a capron fiber with its ends fastened to a bracket and drawn out in the middle with a lever attached to a cylindrical plate spring. A change in the humidity causes the capron thread to expand or contract, and the lever con-

TABLE 7.2

Relative Humidity Determined from the Readings on a Psychrometer

Wet-bulb thermometer reading	Difference in readings on dry-bulb and wet-bulb thermometers, °C																					
	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	
0	100	90	81	73	64	57	50	43	38	34	26	20	16	11	7	3	—	—	—	—	—	
1	100	90	82	74	66	59	52	45	39	33	29	23	19	15	11	7	—	—	—	—	—	
2	100	90	83	76	67	61	54	47	42	36	31	26	23	18	14	10	—	—	—	—	—	
3	100	90	83	76	69	63	56	49	44	39	34	29	26	21	17	13	10	—	—	—	—	
4	100	91	84	77	78	64	57	51	46	41	36	32	28	24	19	14	11	—	—	—	—	
5	100	91	85	78	71	65	59	54	48	43	39	34	30	27	23	19	17	13	10	—	—	
6	100	92	85	75	72	66	61	56	50	45	41	35	33	29	26	22	19	16	13	10	—	
7	100	92	86	79	73	66	62	57	52	47	43	39	35	31	28	25	22	18	15	12	11	
8	100	92	86	80	74	67	63	58	54	49	45	41	37	33	30	27	25	21	18	15	14	
9	100	93	86	81	75	70	65	60	55	51	47	43	39	35	32	29	27	24	21	18	17	
10	100	94	87	82	76	71	65	61	57	53	48	45	41	38	34	31	28	26	23	21	19	
11	100	94	88	82	77	72	67	62	58	55	50	47	43	40	36	33	30	28	25	23	20	
12	100	94	88	82	78	73	68	63	59	56	52	48	44	42	38	35	32	30	27	25	22	
13	100	94	89	83	78	73	69	64	61	57	53	50	46	43	40	37	34	32	29	27	24	
14	100	94	89	83	79	74	70	66	62	58	54	51	47	45	41	39	36	34	31	29	26	
15	100	95	89	84	80	75	71	67	63	59	55	52	49	46	43	41	37	35	33	31	28	
16	100	95	90	84	80	75	72	67	64	60	57	53	50	48	44	42	39	37	34	32	30	
17	100	95	90	84	81	76	73	68	65	61	59	54	52	49	46	44	40	39	36	34	31	
18	100	95	90	85	81	76	74	70	66	62	59	56	53	50	47	45	42	40	37	35	33	
19	100	95	91	85	82	77	74	70	68	63	60	57	54	51	48	46	44	41	39	37	34	
20	100	95	91	86	82	78	75	71	67	64	61	58	55	53	49	47	44	43	40	38	36	
21	100	95	91	86	83	79	75	71	68	65	62	59	56	54	51	49	46	44	41	39	37	
22	100	95	91	87	83	79	76	72	69	65	63	60	57	55	52	50	47	45	42	40	38	
23	100	96	91	87	83	80	76	73	69	66	63	61	58	56	53	51	48	46	44	43	41	
24	100	96	92	88	84	80	77	73	70	67	64	62	59	56	53	52	49	47	44	42	40	
25	100	96	92	88	84	81	77	74	70	68	65	63	59	57	54	52	50	47	45	44	42	

verts the thread movements into circular motions of a light-weight pointer fixed with a holder in the middle of the spring. The pointer indicates the relative humidity on the uniform scale, which is a substantial advantage of the instrument; the uniformity of the scale is due to the arrangement of the moving system as described above. Here the ratio between the deflection of the capron thread and its length for each reading of the relative humidity is a strictly definite value.

This hygrometer can measure the relative humidity in the range between 30 and 100% to within $\pm 10\%$.

In use are also hygrometers suited for the measurement and control of the humidity of air and other gases, which are sensitive elements produced from a dielectric whose composition includes a substance with a highly pronounced electrolytic conductivity. A degreased cellophane film (0.05 mm thick, 0.5 mm wide and 2 mm long) glued to copper electrodes and impregnated with a 5-% lithium chloride solution makes a popular hygrometer. As the air humidity changes, the moisture content of such an element quickly comes to equilibrium with the moisture content of the surrounding air. The moisture content in turn heavily affects the element resistance. So, connecting the hygrometer in an appropriate measuring circuit (commonly an a.c. circuit), we can measure the air humidity. Such a hygrometer can also serve as a humidity sensor in automatic moisture control systems. Hygrometers can be made from a porous ceramic material impregnated with lithium chloride or potassium bichromate (for service at high temperatures and humidities). In use are also hygrometers where the humidity sensor is a thermometer whose bulb is wrapped in a wick impregnated with a lithium chloride solution. The wick is fitted with two electrodes across which a.c. voltage is impressed. The current that passes through the wick depends on the wick resistance which, in turn, is a function of the moisture content. The dissipated power heats up the wick until the processes of water evaporation and absorption come to dynamic equilibrium. The equilibrium temperature of the wick determines the absolute humidity of the air.

The electrical characteristics of materials are commonly determined in a few hours' time t (24 to 28 h and above)

after exposure to the humid atmosphere which must have a specified relative humidity φ and temperature T . The values of t , φ , and T and also the quantities being measured are given in the standard or test specifications on a material.

7.4. Testing at Decreased Air Pressure

A decrease in air pressure with increasing altitude entails a reduction in the ambient temperature within the confines of the Earth's dense atmosphere.

Tests on specimens at low pressures and various temperatures (both positive and negative) are made in the thermal

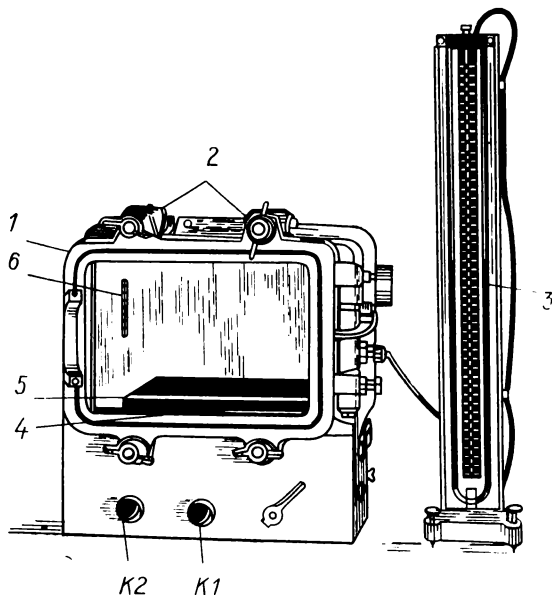


FIG. 7.7. Thermal vacuum chamber. General view

vacuum chambers; specimens placed in such a chamber can also be tested for resistance to vibration. One of the designs of a thermal vacuum chamber is shown in Fig. 7.7. This is a cast metal box with outside ribs to impart rigidity. The front wall has a hinged window 1 to allow access to and

take readings from the instruments placed inside the chamber. Four swing bolts 2 with wing nuts tightly clamp the window to the side walls and thus seal the chamber.

A screen partition divides the chamber into two compartments. The lower compartment contains an electric heater spiral-wire element that can raise the air temperature in the chamber to plus 50°C. Alcohol forced through a pipe coil ensures control over temperatures from 0 to 20°C, and dry ice placed on a pan inside the lower compartment can keep the temperature below zero. The parts to be tested are put into the upper compartment on a support 5 fastened to a shake platform 4. The air temperature is measured with a thermometer 6 or thermocouple. The glass of the sight window is rubbed up with a special grease, or a pan with calcium chloride is set in the chamber to keep the glass from dimming with moisture. The chamber is connected with a manometer 3 and a vacuum pump (both located outside the chamber) through a hose by means of a coupling and a tee-joint. Two needle valves *K1* and *K2* are positioned on the front wall of the chamber. The valve *K1* mounted on the line running from the pump to the chamber and manometer, controls the rate of air evacuation from the chamber. The valve *K2* connects the chamber with the atmosphere. The electric motor of the shaker, lighting lamps, and electric heater draw power from an a.c. supply. Leads pass into the chamber through air-tight bushing insulators. The chamber also has two air-tight high-voltage bushings intended for testing materials for dielectric strength.

A difference $\Delta p'$ between the mercury levels in the left and the right leg of the manometer 3 determines the difference between the pressure in the chamber and that of the ambient air. It is quite possible to use other pressure gages apart from the mercury type. Since the volume of mercury in the manometer tube varies with the temperature of the ambient air, the manometer readings should be corrected for a temperature-variation error δ_t , as the temperature becomes different from zero. The manometer reads pressure in pascals (in millimeters of the mercury column).

A listing of temperature-variation error corrections, δ_t , for every 5°C deviation of the air temperature from the reference value (0°C) appears in Table 7.3. The correction

TABLE 7.3

Altitude-Pressure Table

$\Delta p'$, mm Hg	H , m	δ_t , mm Hg per 5°C	$\Delta p'$, mm Hg	H , m	δ_t , mm Hg per 5°C	$\Delta p'$, mm Hg	H , m	δ_t , mm Hg per 5°C
0	0	0	220	2 789	0.2	440	6 722	0.4
10	111		230	2 937		450	6 948	
20	223		240	3 085		460	7 180	
30	338		250	3 138		470	7 420	
40	453		260	3 392		480	7 665	
50	570		270	3 548		490	7 918	
60	688		0.3	280	3 708	0.5	500	8 178
70	807			290	3 870		510	8 447
80	928			300	4 036		520	8 725
90	1 050			310	4 203		530	9 010
100	1 173	320		4 376	540		9 310	
110	1 298	330		4 551	550		9 615	
120	1 425	340		4 729	560		9 937	
130	1 553	350		4 908	570		10 270	
140	1 683	360		5 091	580		10 620	
150	1 815	370		5 279	590		10 982	
160	1 949	380		5 470	600		11 370	
170	2 084	0.2	0.4	390	5 670	610	11 774	
180	2 220			400	5 870	620	12 215	
190	2 360			410	6 077	630	12 682	
200	2 500			420	6 286			
210	2 643			430	6 502			

depends on the height of the mercury column, therefore the table gives the correction values for various readings of $\Delta p'$ taken from the manometer scale. If the temperature of the ambient air (the temperature of mercury) is above zero, the correction is negative (to be subtracted from the readings), and vice versa.

It is also necessary to introduce a correction for the deviation of the atmospheric pressure at the Earth's sur-

face from the normal pressure. The correction δ_n is

$$\delta_n = 760 - p_0 \quad (7.3)$$

where p_0 is the atmospheric pressure at the Earth's surface at the time of testing. The correction $\delta_n > 0$ if p_0 is above the normal, and $\delta_n < 0$ if $p_0 < 760$ mm Hg.

The readings on the manometer, including the corrections

$$\Delta p = \Delta p' \pm \delta_t \pm \delta_n \quad (7.4)$$

From the altitude-pressure table we can find the altitude above sea level H for the value of Δp . This table is calculated by the formulas

$$p = p_0 \left(\frac{T_0 - T_{gr}H}{T_0} \right)^{\frac{1}{RT_{gr}}} \quad (7.5)$$

$$p = p_{11} e^{-\frac{H+11\,000}{RT_{11}}} \quad (7.6)$$

where p_0 is the atmospheric pressure at the Earth's surface; p is the air pressure at altitude H ; T_0 is the absolute air temperature at the Earth's surface; R is the gas constant; T_{gr} is the vertical temperature gradient, that is, a change in temperature per unit altitude; p_{11} and T_{11} are the pressure and temperature respectively at an altitude of 11 000 m. The first formula holds for the troposphere that extends outward about 11 000 m from the Earth's surface, and the second for the stratosphere.

The table is compiled using the following initial data: $p_0 = 760$ mm Hg, $T_0 = 298$ K, $R = 29.27$ m/K, $T_{gr} = 0.0065$ K/m, $T_{11} = 216.5$ K, and $p_{11} = 169.6$ mm Hg.

For determining a temperature T_H at a given altitude H (in meters), we have to subtract the temperature drop $T_{gr}H$ from the absolute temperature T_0 at the Earth's surface. So, for the standard conditions

$$T_H = 298 - T_{gr}H = 298 - 6.5 \times 10^{-3}H \quad (7.7)$$

The temperature T in degrees of the centigrade temperature scale is

$$T = T_H - 273$$

The thermal vacuum chamber described above is adaptable to testing materials under the combined effect of high voltages and low air pressures, varying at the same time the ambient air temperature and subjecting the specimens to vibration if necessary. Low pressure tests allow determining the resistance of materials to surface discharges and estimating certain characteristics of air-tight connections and components of apparatus.

MECHANICAL CHARACTERISTICS

8.1. General

Mechanical testing of materials, including insulating materials, is of much practical significance since in operation of various machines and apparatus the parts made from these materials can be subjected to rather high mechanical loads.

As regards the mechanical behavior of materials in response to the applied loads, all the materials may be divided into three main groups: elastic, plastic, and brittle.

Elastic materials, of which rubber is an example, heavily deform under the applied force; on removing the load earlier than when the specimen rupture ensues, the specimen tends to resume its form.

Plastic materials are also susceptible to rather heavy deformations, but, unlike elastic materials, these materials retain the dimensions and form they have acquired under the applied force. An example is wax.

Brittle materials break up under a certain load without showing any noticeable deformation at all. Examples of these materials are glasses and ceramics.

The above classification is not quite strict and rather arbitrary since many materials possess intermediate properties and cannot be placed into any of the groups whatever. Of importance is also the fact that the mechanical properties of many materials strongly depend on temperature. At sufficiently low temperatures practically all materials become brittle. Thus at the temperature of liquid air, rubber turns out to be so brittle that the specimen splits into small pieces on hitting. On the contrary, glass heated to a high temperature becomes readily moldable.

The mechanical properties of a variety of hygroscopic materials, such as paper, strongly change with humidity. That is why mechanical tests must use specimens conditioned at a definite humidity and temperature.

The kind of applied load has a great bearing on the behavior of the material subjected to the mechanical stress. There are static, uniformly growing, loading and dynamic loading applied instantaneously as a hit or impact. Brittle materials rupture quite easily under impact loads, though many of these exhibit good resistance to static loads. Plastic materials often gradually deform (flow) under a comparatively small load applied for a long time. This deformation under the action of a sustained force is known as plastic flow. For example, a polyisobutylene specimen suspended at one of its ends for a few hours can noticeably deform under gravity even at normal temperature.

For anisotropic materials, such as laminates, the direction of the applied force has a great effect on their mechanical properties. Apart from the factors considered, other influences, such as fatigue, affect the materials. Mechanical testing is basically directed at determining the breaking stresses and attendant strains in the material under test.

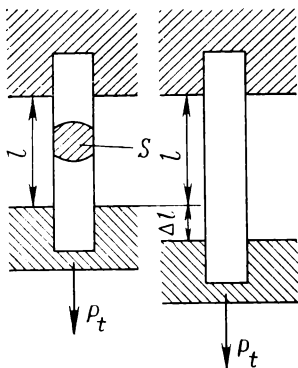


FIG. 8.1. Illustrating the test on a specimen for tensile strength

8.2. Strength in Rupture, Compression and Cleavage

If a specimen of cross section S takes a smoothly growing tensile force (Fig. 8.1), the breaking stress P_t causes the specimen to rupture. The tensile strength is found from the expression

$$\sigma_t = P_t/S \quad (8.1)$$

In testing a material for rupture strength, it is possible to estimate at the same time its percentage elongation

$$\lambda = \frac{\Delta l}{l} 100 \quad (8.2)$$

where l is the free length of a specimen before applying the load (that is, the distance between the grips which

tightly hold the specimen); and Δl is the absolute elongation of the specimen at the moment just prior to rupture (Δl and l shall be measured in the same units of length).

The compressive strength σ_c (in pascals) of a test specimen broken down under a uniformly growing crushing force is estimated by the formula

$$\sigma_c = P_c/S \quad (8.3)$$

where P_c is the crushing load in static compression, N; and S is the specimen cross section prior to test, m^2 . The height of a test specimen shall be comparable to its lateral dimensions to exclude longitudinal bending.

Tensile and compression tests make use of special apparatus such as tensile-testing machines, testing presses, and dynamometers. A tensile-testing machine has grips for holding the specimen to be subjected to a constant rate of stressing, and load- and strain-indicating devices. More advanced testing machines incorporate a device which automatically draws a graph relating the strain to the load (stress) carried by the specimen until it ruptures. Tensile-testing machines are available in a variety of overall dimensions, rated at loads from hundredths of a newton (dynamometers for estimating the strength of fiber) to many kilonewtons. These machines must meet the requirements prescribed in pertinent standards. For example, the technical characteristics of machines designed to test plastics for tensile strength must satisfy the requirements as stipulated under Soviet State standard 20480-75. Tensile-testing machines can be driven manually or electrically. Electric motor-driven machines are more preferable since they allow for more uniform stressing at a definite rate.

Figure 8.2 illustrates schematically a small-load hand-driven tensile-testing machine. Weight 1 is fastened to a long arm 5 of an unequal-arm lever that can turn about its axis in the upper part of the machine pedestal. A flywheel turned with a handle 15 transmits the load via a pair of bevel pinions 16 and a vertical screw shaft 14 to a test specimen 12 tightly fixed in grips 11 and 13. An upper grip is suspended from one end of a flexible chain, whose other end is attached to a segment-like arm 8 of the lever. As the load on the specimen grows (on rotating the flywheel with the handle 15), the lever gradually swings about its axis,

and the moment of weight *I* that counterbalances the moment of load on the specimen, rises. At the instant when the specimen ruptures, the weight *I* does not move into the initial position but remains still because a retaining pawl *3* attached to the long arm *5* of the lever bears into a tooth of a

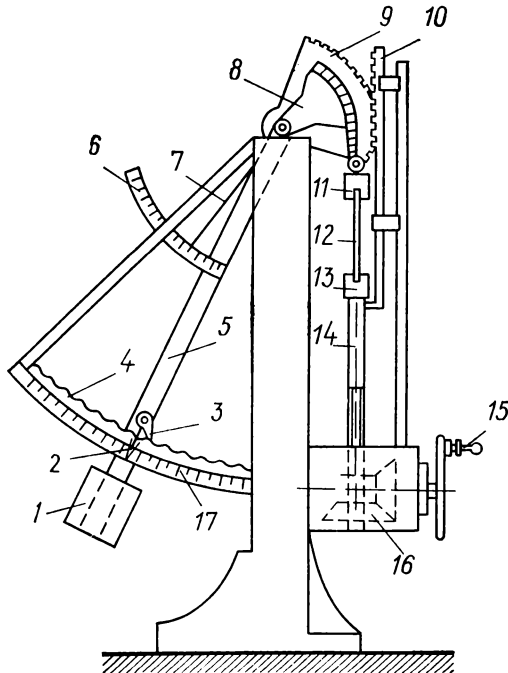


FIG. 8.2. Hand-driven tensile-testing machine

segment rack *4* having on its surface a scale *17*. A pointer *2* fixed to the long arm indicates the strain on the specimen at any time of the test. The weight *1* is replaceable; the same machine can use any weight for testing specimens at various values of the maximum tensile force. Of course, the reading taken on the scale *17* needs correction with each replacement of the weight.

An elongation of the specimen is read from a second segment scale *6*. This scale is fixed to and moves together with

the arm 5. Its pointer 7 is connected to the lower grip 13 via a gear segment 9 and gear rack 10.

An electric motor-driven tensile-testing machine is shown in Fig. 8.3.

Compression tests are made on special presses or universal machines designed for various types of mechanical

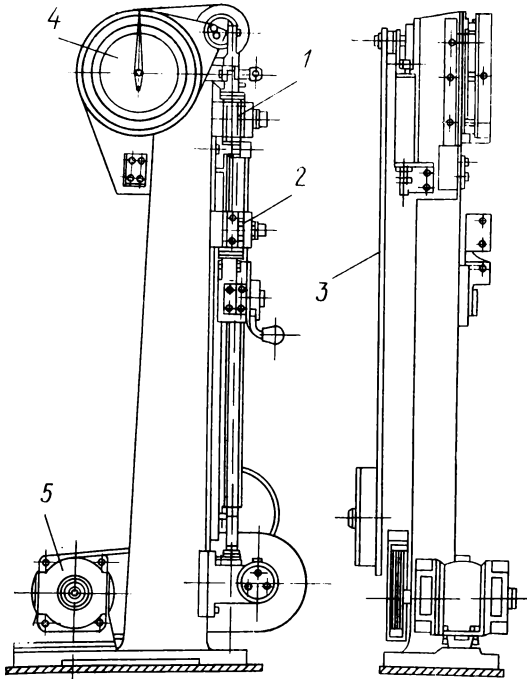


FIG. 8.3. Motor-driven tensile-testing machine
1 and 2—grips; 3—lever with weight; 4—scale; 5—electric motor

testing. In the absence of such machines, the compression test can be performed on a common tensile-testing machine complete with appropriate fixtures. Fig. 8.4 shows an arrangement (reverser) that permits conducting compression tests on a tensile-testing machine. Steel plates 1, 2, 3, and 4 are joined together with two pairs of bolts *a* and *b*. The bolts *a* rigidly connect plates 1 and 3 with each other and

freely pass through the holes drilled in the plate 2, while the bolts b that loosely go through the holes made in the plate 3 rigidly fix together the plates 2 and 4. On fasten-

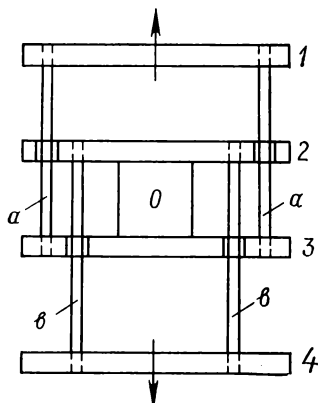


FIG. 8.4. Schematic arrangement of a reverser

ing the plates 1 and 4 in the grips of the machine, a specimen O clamped between the plates 2 and 3 can be tested for resistance to compression.

It is important to note that unlike, for example, the metals which have σ_t , σ_c , and bending strength σ_b of the same order of magnitude, some insulating materials such as glasses and ceramics show a much larger strength in compression than in tension or bending. Compression tests thus often require a machine of a much higher load rating than when testing the same insulating material for tensile strength.

Both compression and tensile test specimens shall have quite a definite shape and dimensions as specified by the standards for testing the appropriate materials. Test specimens of thin-sheet materials, such as paper, pressboard, film, cloth, varnished cloth, and others, are made in the form of strips. For example, tensile test specimens of paper and pressboard are strips 15 mm and 50 mm wide respectively. These specimens, like the specimens of fiber, tape, and wire, are fixed in the ordinary grips of the testing machine. The gripping surfaces are made checkered to prevent slippage of the specimen during the test; if necessary, a soft spacer is interposed between the specimen and the grip jaw. The specimen shall tear between the grips. If the specimen ruptures at the place where it goes out of the grip, the test cannot be considered reliable. Care should be exercised to avoid misalignment of the specimen's long axis with an imaginary line between the grips when fastening the specimen. Specimens of paper, film, and other similar materials are cut out with a guillotine such as used for trimming photographs.

In conducting rupture tests on paper, textured film, and other anisotropic sheet materials, one should differentiate between the specimens cut lengthwise the roll and those cut crosswise. The former show a higher rupture strength, but then the latter give a larger percentage elongation.

Paper and some other materials are sometimes tested for breaking length L apart from the tensile strength. This is the largest length of a strip or thread (of the same cross section over the entire length), suspended at one of its ends, that can still withstand the effect of gravity. The quantity L is related to the tensile strength σ_t and the density ρ of a material by the expression

$$L = \sigma_t / \rho \quad (8.4)$$

It is practically convenient to calculate L (m), when running the rupture test, from the breaking load P_t (N) and the mass G (kg) of the strip of length l (m) between the grips:

$$L = P_t l / G \quad (8.5)$$

If we know the mass g (kg) of 1 m² paper, then

$$L \approx 10P_t / bg \quad (8.6)$$

where L is the breaking length, m; b is the strip width, m; and P_t is the breaking load, N.

In a number of cases, test procedures require that specimens have a special form and the respective shape of grips of the tensile-testing machine. Thus tension specimens of plastics, ceramics, cement, and other materials have the "figure-eight" shape with expanded ends and a narrowed middle portion. The dimensions of a specimen for testing plastic materials are given in Fig. 8.5. The tensile strength σ_t for these specimens is the ratio of the breaking load to the least cross-sectional area (in the middle of the neck) measured prior to test. For the specimen shown in Fig. 8.5, this area is obviously equal to $25 \times 6 = 150 \text{ mm}^2 = 1.5 \times 10^{-4} \text{ m}^2$. The specimens of polymer film about 1 mm thick shall have the shape of a rectangular strip 10 to 25 mm wide and 150 mm long. Strips are cut both lengthwise and crosswise the direction of film drawing. At least five specimens shall be tested for each sample, the number being specified in the pertinent standard for a material.

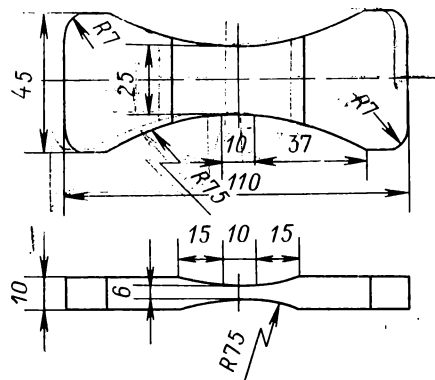


FIG. 8.5. Tension specimen for plastic materials

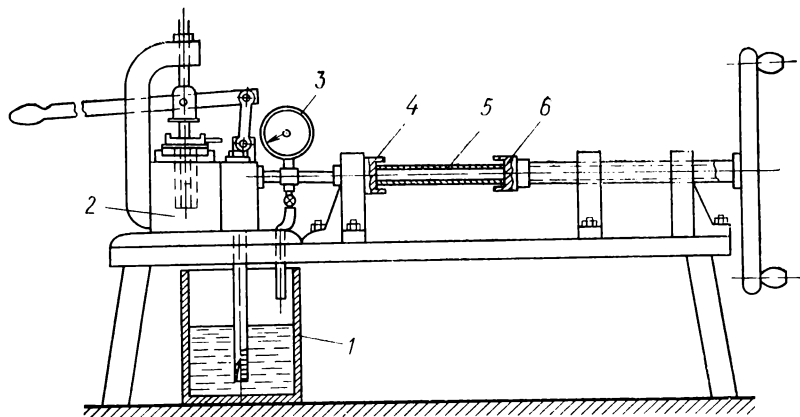


FIG. 8.6. Test bench for testing a tubular specimen for rupture strength under hydraulic pressure

Tests for compression strength are usually made on specimens shaped like a cube or cylinder with the height equal to or somewhat larger than its diameter. For instance, a standard compression-test specimen for plastics is a cylinder 10 mm in diameter and 15 mm in height. For laminated plastics, this is a 10 by 10-mm base paralleliped 15 mm

in height (it is an accepted rule that a compression-test specimen for laminates shall be not less than 15 mm).

Laminated plastics are sometimes tested for resistance to cleavage (splitting) apart from resistance to compression (across the layers). The test procedure involves pressing a

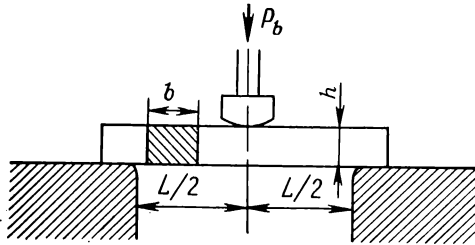


FIG. 8.7. Illustrating the test on a specimen for bending strength

wedge of definite form into the end face of a strip (along the layers). The force at which the wedge splits the strip is a measure of the cleavage strength.

Tubular materials (for example, wound pieces) are tested for rupture strength under hydraulic pressure as illustrated in Fig. 8.6. A 300 to 400-mm long tubular specimen 5 is fastened in grips 4 and 6 and a pump 2 is actuated to draw oil from a tank 1 and force it inside the specimen. The oil pressure indicated by a pressure gage 3 is raised at a rate of 2 to 2.5 MPa/s. The tensile strength (in pascals) of the tubular material is

$$\sigma_t = p \frac{d}{D-d} \quad (8.7)$$

where p is the gage pressure at which the specimen ruptures, Pa; D and d are the outside and the inside diameter of the tube.

8.3. Flexural Strength at Static and Impact Loads

As noted earlier, the flexural (bending) strength depends on the rate of growth of the applied force. This calls for determining the strength both in static and in dynamic (impact)

bending. The standard specimen is a bar of rectangular cross section freely supported at two points. The uniformly growing force is applied from above at a point midway between the points of support (Fig. 8.7). The strength σ_b (in pascals) is

$$\sigma_b = 1.5 \frac{P_b L}{bh^2} \quad (8.8)$$

where P_b is the breaking static load, N; L is the distance between the points of support, m; b is the bar width, m; and h is the bar height (thickness), m.

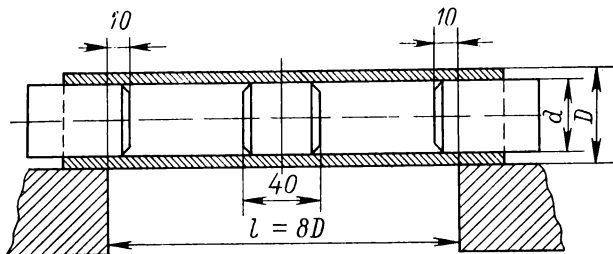


FIG. 8.8. Illustrating the test on a tubular specimen for bending strength

Static bending test methods use the same tensile-testing machines and testing presses as the methods for determining the strength at rupture and in compression. Bending-test specimens vary in shape and size.

In testing plastics for static bending strength, the standard specimen shall be about 80 mm in length L , 10 mm ± 0.5 mm in width b , and 4 mm ± 0.2 mm in thickness h . Where standard specimens are not available, bars not less than 20 mm in length L may serve as substitutes, the width of each being chosen to suit its thickness:

Bar thickness h , mm	1 to 3	3 to 5	5 to 10
Bar width b , mm	25 ± 0.5	10 ± 0.5	15 ± 0.5

Tubular materials are tested for flexural strength as shown in Fig. 8.8. As seen, the tube shall have plugs driven into its central portion and fixed at its ends. The rod that transmits the bending force shall have a rounded tip of 15 mm radius. The distance between the points of support shall be eight times the tube's external diameter. The force

is raised at a rate of 2 500 N/min. The bending strength of the tubular material is calculated by the formula

$$\sigma_b = \frac{8P_b l D}{\pi (D^4 - d^4)} \quad (8.9)$$

where P_b is the force that produces rupture, N; l is the distance between the points of support, m; D and d are the external and the internal diameter of the tube, m.

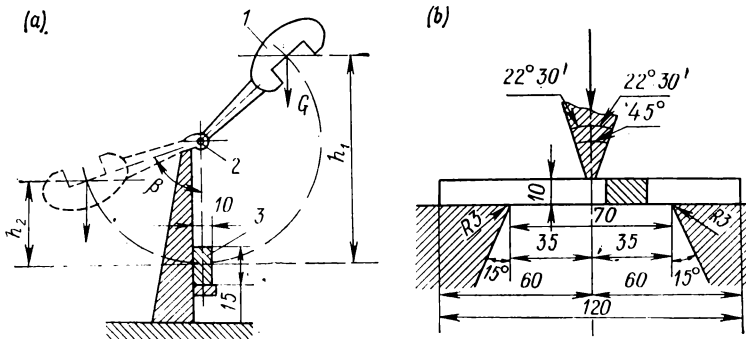


FIG. 8.9. Charpy impact machine (a) and position of the striker relative to the specimen at the moment of impact (b)

Impact test methods for determining the impact strength of solid materials use a standard pendulum-type impact machine (Charpy impact machine), whose arrangement appears in Fig. 8.9a. A heavy pendulum 1 has a wedge-like striker tapered to an included angle of 30 or 45° and rounded to a radius of 2 or 3 mm (Fig. 8.9b). The pendulum swings about its axis 2. Its center of gravity coincides with the center of the striking edge. The pendulum is kept in the initial position (as shown by solid lines in Fig. 8.9a) with a catch. A specimen 3 is placed so that it lies on the arc of travel of the pendulum. On releasing the catch, the pendulum swings down, breaks up the specimen in one blow, and goes upward to a position as shown by dot-and-dash lines. The mutual arrangement of the specimen and the striker at the instant of impact is illustrated in Fig. 8.9b, which shows the striker section along the plane perpendicular to the long axis of the pendulum.

The impact strength of a material in kilojoules per square meter (kJ/m^2) is the ratio of the energy expended by the machine in breaking the specimen to its cross-sectional area

$$a = \frac{10^{-3}G(h_1 - h_2)}{F} \quad (8.10)$$

where G is the pendulum mass, N ; h_1 is the height of the pendulum's center of gravity in the initial position, m ; h_2 is the pendulum's center of gravity after breaking the speci-

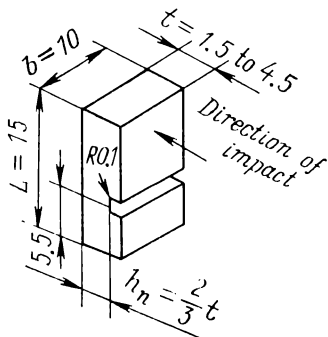


FIG. 8.10. Notched specimen of plastic materials for determining impact strength using the Dynstat-type device

men; m ; F is the cross-sectional area of the specimen, m^2 . For the standard bar, $F = 1.5 \times 10^{-4} \text{ m}^2$, with the width equal to 0.015 m and thickness to 0.01 m.

Impact-testing machines (Soviet State Standard 10708-76) can store a potential energy from 4.9 to 2 451.6 J; replaceable pendulums possess a store of energy from 2.45 to 980.6 J. The store of potential energy shall not deviate from the set value in excess of $\pm 5\%$. The pendulum speed at the instant of impact is 3 to 5 m/s. Given a definite initial position of the pendulum, we can determine the value of $G(h_1 - h_2)$ from the pertinent tables for each angle of the pendulum's upward swing read from the scale. For materials showing a very high resistance to breakage, the test specimen shall have a notch cut at the place of impact.

In use is also a pendulum device of the Dynstat type (Soviet State Standard 14235-69) for testing plastics 1.5 to 4.5 mm thick. The width and thickness of a specimen shall be accurate to 0.01 mm; the tests sometimes require notched specimens (Fig. 8.10), the notch being cut to a depth of not more than one-third the total thickness of the specimen.

The impact testing device is equipped with a set of replaceable weights and appropriate scales, so that the device can store energy of the following values: 0.5, 1, and 2 J. The pendulum is raised through an angle of 90° and fixed in position with a catch. The specimen is then clamped in the grip, the pendulum smoothly released from the catch, and the rupture work A done on the specimen is noted on the scale; the work must range from 10 to 80 % of the total energy stored by the device for the given mass of the weight. The speed of the pendulum at the instant of impact is 2.2 m/s. The impact strength of the material tested is found by the formulas

$$a_f = \frac{A_f}{bh_f}, \quad a_n = \frac{A_n}{bh_n} \quad (8.11)$$

where A_f and A_n are the rupture work done on the notch-free specimen and on the notched specimen respectively; b is the specimen width, m; and h_f and h_n are the thickness of the notch-free specimen and the thickness at the place of notch respectively, m. It is sometimes useful to know the impact strength reduction ratio determined by the formula

$$K = a_n/a_f \quad (8.12)$$

where a_f and a_n are the impact strength determined as the arithmetic mean of all the measurement results for the notch-free and notched specimens respectively.

The smaller the impact strength of a material, the higher its brittleness. For elastic materials, the impact strength method of test is impracticable since the specimen bends and shifts from its place under impact without being ruptured.

8.4. Hardness and Abrasive Resistance

Hardness is the property of a material that permits its surface layer to withstand the strain caused by dynamic or static compressive forces. Abrasive resistance, or wearability, is the property of a material that enables it to resist the mechanical wear under the action of friction forces. There are several well-known methods of estimating hardness.

The Brinell ball method (ball indentation method) determines the value of hardness by pressing a 5-mm diameter steel sphere with a special press into the surface of a test specimen placed on a steel plate (Fig. 8.11). The load P

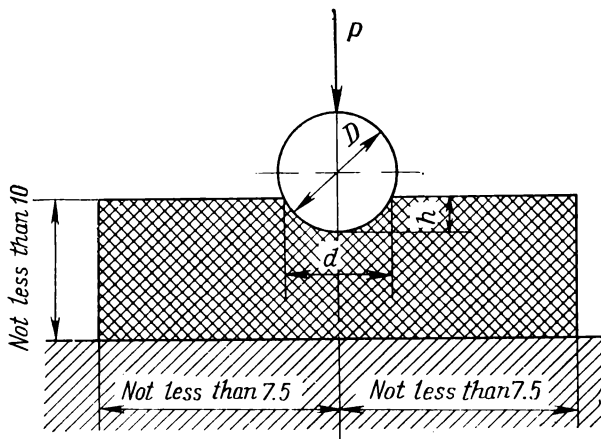


FIG. 8.11. Illustrating the Brinell hardness test

acting on the ball continuously grows for a few seconds to a maximum value and then remains constant for a standard length of time (Soviet State Standard 4670-77). After removal of the pressure, a special device measures the depth of indentation of the ball, h (mm). The Brinell hardness BH is evaluated as the quotient of the force applied to the ball by the area of the spherical surface of indentation left on the specimen:

$$BH = \frac{10P}{\pi dh} \quad (8.13)$$

where BH is the Brinell hardness, MPa; P is the force on the ball, N; d is the ball diameter, mm; and h is the depth of indentation, mm. The hardness-test specimens shall have a thickness of 4 to 10 mm. They may be composed of a pileup of several pieces (but not more than three); the ball indentation on the specimen surface shall terminate at least 5 mm short of the specimen edges. The maximum force applied to the ball shall be such that in a 30 seconds' time the

penetrator can produce an indentation 0.15 to 0.35 mm deep. This force may range from 49 to 1 470 N.

The Kuznetsov method (pendulum hardness test method) measures the hardness of brittle and inflexible materials

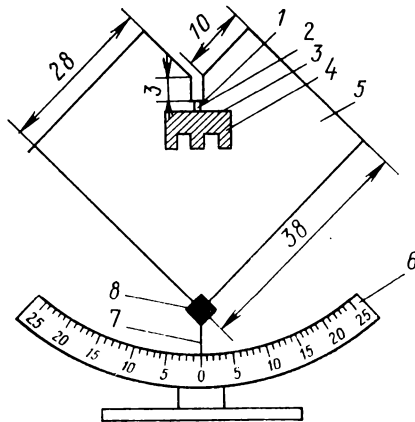


FIG. 8.12. Kuznetsov pendulum. Schematic

(such as glass), for which materials the Brinell method is inapplicable (Fig. 8.12). A specimen 3 under test is secured in place on a support 4 and then a pendulum plate 1 with its two props 2 is set up on the specimen surface. The pendulum is a light metallic frame with a weight 8 suspended from the pendulum in its lower part. The pendulum plate props are steel balls or diamond stones pointed to an angle of 90°. The pendulum is set in oscillatory motion. The amplitude of the swing is indicated by a pointer 7 on scale 6. The smaller the test specimen hardness, the faster the pendular oscillations die out. The Kuznetsov method is also suitable for measuring the hardness of varnish film and mica.

The Shore method (rebound test method) finds use for testing brittle materials. The tester is the Shore scleroscope in which a steel ball falling by its own weight from a standard height strikes the surface of the specimen under test and rebounds. The height of rebound is a measure of the hardness of the material in question.

There are a number of test devices for evaluating the resistance of materials to abrasion. A scraper-type device, whose circuit diagram is shown in Fig. 8.13, is designed to measure the abrasive resistance of enamel-insulated wire

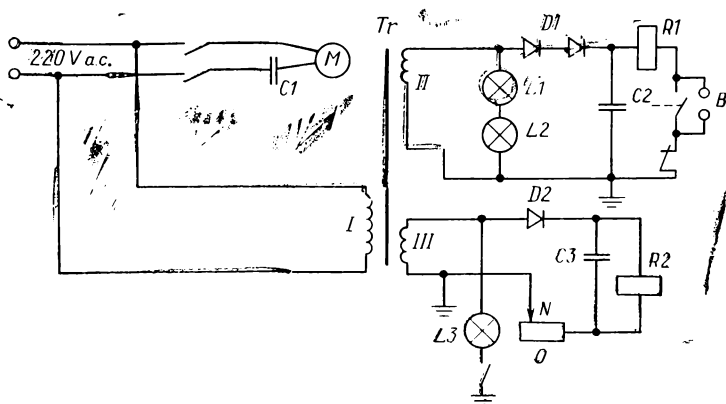


FIG. 8.13. Circuit diagram of a tester for determining the abrasive resistance of enamel-insulated wire

Tr—transformer; *I*, *II*, and *III*—transformer windings, 220 V, 24 V, and 14 V; *L1*, *L2*, and *L3*—signal lamps; *C1*—paper capacitor, 2 μ F; *C2* and *C3*—electrolytic capacitors, each 100 μ F; *R1* and *R2*—d.c. relays; *D1* and *D2*—selenium rectifiers to feed relays *R1* and *R2*; *B*—start button; *M*—electric motor; *O*—specimen; *N*—needle

(State Standard 15634.2-70). The tester consists of an electric motor *M* with a reduction gear and a cam, a scraper with a 0.66-mm dia. needle *N* at its end, a set of weights to produce the desired pressure on the needle, fixtures to fasten the specimen tested, relays *R1* and *R2* to disconnect the motor and the counter of the needle's reciprocating movements as the needle comes in contact with the wire. In testing, the bare end of wire must be connected to one pole of a d.c. source, and the needle to the other pole. The force on the needle may range from 0.98 to 5.88 N depending on the type of insulation and the gage of wire under test. The needle is allowed to land gently on the specimen and the motor is turned on to cause the needle to reciprocate and wear out the surface within the bounds of 6 or 10 mm. The speed of motion of the needle is 60 or 12 double paths in a minute. The d.c. voltage between the needle and the wire specimen

is 12 V. As the needle penetrates deep into the insulation and comes in electric contact with the wire, the device is automatically disconnected from the supply. The counter indicates the number of reciprocating movements of the

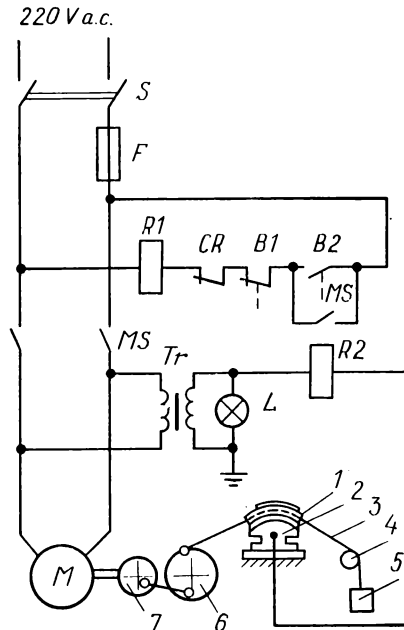


FIG. 8.14. Circuit diagram of a tester for determining the abrasive resistance of electrical insulating tubes

F—fuse; *MS*—magnetic starters; *R1* and *R2*—resistors; *CR*—current relay; *Tr*—step-down transformer; *M*—electric motor; *B1* and *B2*—start and stop buttons; *S*—switch; *L*—signal lamp; 1—tubular specimen; 2—support; 3—wire rope; 4—disk; 5—weight; 6—guide roller; 7—reversing mechanism

needle up to the moment of complete abrasion. This number is a measure of the abrasive resistance, and must be not lower than the value stipulated in the standard or specifications on the wire tested.

Electrical insulating tubes cylindrical in shape (State Standard 17675-72) are tested for resistance to wear with a device whose diagram is given in Fig. 8.14. The tubular specimen is fixed to a support with a holder and subjected

to abrasion by a wire at a load of 196.6 N. The wire reciprocates to cover a path on either way of 85 mm. The speed of wire is 50 reciprocating movements in a minute. The speed is indicated by the counter coupled with a reverser mechanism. After the required number of abrasive cycles is completed, the specimen is removed from the support and subjected to testing for dielectric strength. The permissible breakdown voltage is given in the pertinent standard on this type of material.

8.5. Flexibility, Plasticity, and Elasticity

Testing for flexibility involves folding a thin material on itself in the forward and the reverse direction until it ruptures after some number of bends. An example of the tester for estimating the flexibility of some types of insulating paper is a folding machine (folder). The test specimen in the form of a 15-mm wide paper strip is clamped in spring-tensioned grips to keep the specimen under tension, commonly at 0.1 N. The strip is stretched between two pairs of stationary metal rods and passed midway between each pair through a slit in a metal bar which reciprocates and bends the strip now in one direction, now in the other. As it experiences a complex mechanical effect, the paper in the slit creases and gradually loses strength. The moment comes when the strip no longer stands the tension of the springs and ruptures. The number of reverse bends (folds in both directions) of the strip until it breaks up is a measure of its flexibility. The counter indicating the number of bends will stop automatically as the specimen breaks up.

An elastometer is also suitable for measuring the flexibility of a material. In the device schematically presented in Fig. 8.15, the test specimen in the shape of a 25×200 mm strip is fastened vertically in two grips (in two pairs of jaws); the upper jaws can turn around its horizontal axis (running near its edges) through a specified angle, commonly not over 90° . A 0.5-kg weight holder suspended from the lower jaws can carry additional weights (the total mass of the holder with weights is equal to 1 kg). The edge radius of upper jaws is 0.05 mm. The flexibility is expressed through

the number of reverse bends that cause the specimen to rupture.

An elastometer often proves to be a more sensitive tester than a folder. Unlike the folder, the elastometer is more adaptable to evaluating the effect of thermal aging on a decrease

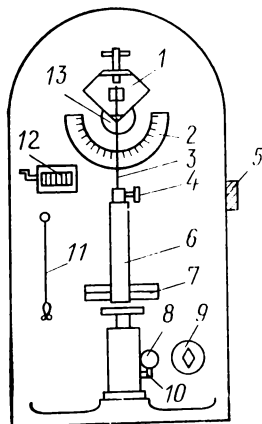


FIG. 8.15. Elastometer. Schematic

1—upper grip turning to desired angle; 2—dial marked in degrees of circle; 3—specimen; 4—lower grip; 5—ring for hand setting of upper grip to zero position; 6—weight holder suspended from lower grip; 7—weight; 8—weight lifter; 9—switch of motor for turning the upper grip; 10—lifter handle; 11—plumb line; 12—counter; 13—shaft of turning mechanism

in the number of reverse bends when testing the specimens of paper, varnished cloth, and other sheet materials.

Plasticity is the property of soft materials (as bitumen and wax) by virtue of which they can be permanently deformed under the applied load. This property is often evaluated by the depth of penetration of the standard needle of a penetrometer into the test specimen under a definite load acting for a standard length of time.

The penetrometer depends for its operation on the relation between the depth of penetration of a solid body of standard form under the applied force into another body and the time of action of this force. The standard needle commonly has a blunted end. For waxes, bitumens, and some resins, the depth of penetration heavily grows with temperature.

Bitumens are also tested for plasticity by stretching a

standard specimen at a definite rate of tension and temperature. The characteristic so obtained is known as ductility. A ductilometer thus determines the stretchability of a specimen, that is, its ability to draw out in the direction of the applied tensile force with corresponding reduction in the cross-sectional area without actual fracture and cracks. It should be kept in mind that ductility is not related directly to the depth of penetration. K

Elasticity is the property of a material that enables it to recover its original size and shape after being strained or deformed.

8.6. Vibration-Resistance Tests

These tests are run with the aim to determine the fitness of a material or component for long-term service under vibration and also estimate changes in its characteristics after subjecting it to short-time vibration.

A vibration test unit shown in Fig. 8.16 comprises a welded framework inside which moves a vertical rod in bearings. A vibratory plate is fixed to the upper end of the rod. The lower end of the rod is rigidly attached to a cam block which consists of two identical gear wheels and two pairs of cams fitted out on the gear shafts. Each cam consists of two segments, one of which is movable. Two cams rotate clockwise and the other two anticlockwise, so that the horizontal components of centrifugal forces are mutually balanced out, while the vertical components impart a vibratory vertical motion to the entire moving system of the machine. The amplitude of vibrations is adjusted by shifting the axes of symmetry of the movable segments relative to those of the stationary segments. The vertical components of centrifugal forces are equalized by a balancing spring. The length of the spring is adjusted with a nut screwed on a sleeve that rests on a plate in the middle portion of the test unit. A cam block pin located in a ball bearing prevents the vibratory system from turning in the horizontal plane; the ball bearing can shift between angle bars secured in the frame. A tachometer with a scale calibrated in hertz reads the vibrational frequency of the system.

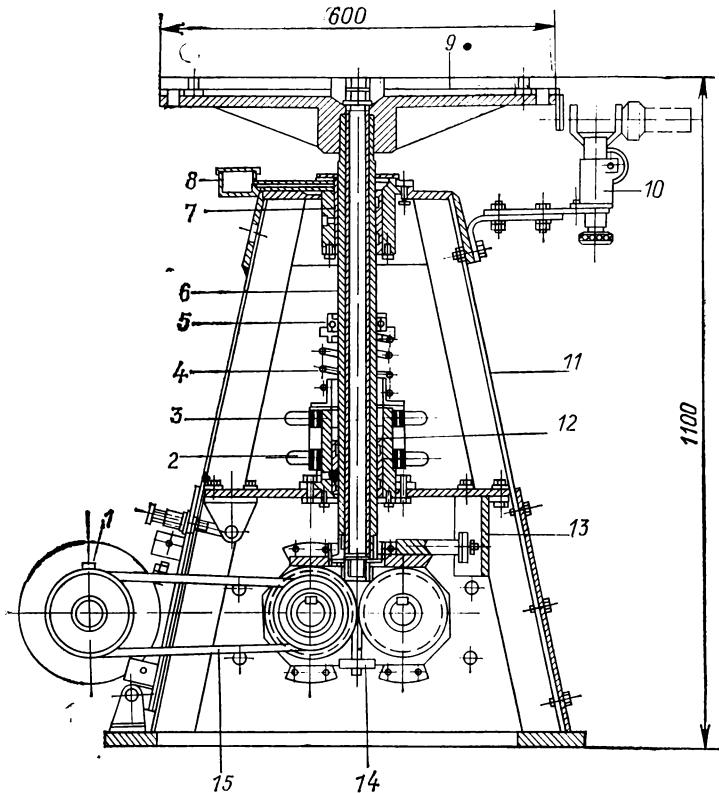


FIG. 8.16. Vibration test unit

1—electric motor; 2—lock nut; 3—lower nut; 4—spring; 5—thrust bushing; 6—shaft; 7—upper bearing; 8—oil cup; 9—vibratory plate; 10—optical micrometer holder; 11—frame; 12—sleeve; 13—guide bearing; 14—cam block; 15—V-belt transmission

The amplitude of vibrations can be observed with a ten-power optical micrometer whose scale permits taking readings accurate to 0.1 mm. The height of a smeared band seen in the micrometer is the double amplitude of oscillations. The vibrational frequency can be controlled in the range from 50 to 500 Hz by adjusting the rotational speed of an electric motor. The double amplitude of vibrations can

be varied from 1 to 10 mm. The test unit is furnished with calibration-check graphs.

The time of testing, vibrational frequency, and amplitude are stipulated in the standard or test specifications. Specimens are fastened on the vibratory table with clamps, screws, by soldering, and other means. After testing, the specimens are checked for mechanical damage and tested for dielectric strength, tightness (for sealed components), and other properties.

A more thorough investigation into the effect of vibration involves long-term testing conducted in the following manner. The specimen to be tested is set up on a vibratory plate and subjected to vibration at a frequency of 45 to 50 Hz and an amplitude of 0.4 mm. The requisite parameters of the specimen are measured every 2 h with the vibratory system in motion. The unit is stopped every 4 h to examine the specimen and measure its parameters. The testing is not terminated until after the appearance of mechanical damage or impermissible changes in the specimen characteristics. A yet more severe test procedure calls for testing at limiting values of frequency and amplitude. The frequency is raised from 30 to 90 Hz at an amplitude of 0.3 mm, following which the amplitude is increased to 0.4 mm and still higher in steps up to 1.4 mm if, of course, the specimen has not failed earlier mechanically or electrically. The desired characteristics are checked at 2-h intervals.

THERMAL CHARACTERISTICS

9.1. General

The characteristics of electrical insulating materials undergo heavy changes as the temperature varies over a wide range, so the materials become hardly suitable for use. Increased temperatures generally impair most important properties of electrical insulation. Consequently, the problem of raising the upper temperature limit of insulation to enable it to endure elevated temperatures without a considerable decrease in operating reliability has an exceptional practical significance. The thermal characteristics include thermal conductivity, softening point, fire point, thermal endurance, thermal shock resistance, and cold resistance.

Thermal conductivity is analogous to the electric volume resistivity of a material.

Thermal endurance is the property of an electrical insulating material which permits it to stand up to enhanced temperatures for a length of time comparable with its service life without failure or impermissible deterioration of important characteristics.

According to thermal endurance, electrical insulating materials used in electrical machines and transformers fall into seven insulation classes (Soviet State Standard 8865-70). Class Y insulation includes cellulose-base and organic-base plastics not impregnated with a bonding substance; the upper operating temperature limit for these materials is 90°C. Class A insulation has an upper temperature limit of 105°C. Class E insulation consists of synthetic fiber, film, resins, and other materials with a limiting temperature of 120°C. Class B insulation consists of materials based on mica, asbestos, and glass fiber, which have a limiting temperature of 130°C. Class F insulation consists of the same materials as given in Class B but impregnated with synthetic

binders, the limiting temperature being 155°C. Class H insulation that includes the same materials as those which enter class F insulation impregnated with silicone binders can withstand temperatures up to 180°C. Class C insulation includes materials whose temperature limit is above 180°C.

As seen, this system of class ratings disregards the conditions at which a particular material has to operate (such as the required service life, electric field, mechanical loads, chemical influences, and radiation). Along with this type of classification, a new approach to thermal evaluation of materials, based on IEC Publication 216 and its further versions, has recently found increasing favour since it gives wider and more comprehensive information on thermal endurance.

In short, the essence of thermal evaluation according to the recommendations of the International Electrotechnical Commission comes to the following. A material or combinations of materials are subjected to thermal aging at a few different temperatures. Test aging of every batch of specimens placed in a special oven is conducted both at an invariable, fixed temperature and at a cyclically varying temperature according to the predetermined procedure if this temperature cycle is more or less specific to the probable operating conditions of the electrical insulation under test. Along with thermal aging, specimens may be simultaneously subjected to other influences such as an electric field, mechanical loads, chemically aggressive media, and radiation either at a constant or at a cyclically varying temperature. The finite "limit" point of aging is a point at which a certain change occurs in a specimen parameter which is considered most important for establishing the serviceability of the material under certain operating conditions. The limit of aging can be ascertained in two different ways. By the first variant, the aging test is terminated as soon as an initial parameter of the specimen alters to a preset value, for example, as its mechanical strength or elasticity falls to 50% of the initial value. In the second variant, aging is stopped as a certain parameter changes to a preset value regardless of its initial value prior to test.

After the aging test is completed the next stage that follows is extrapolation, by formula (9.11), of the test data into an

area of lower temperatures T and longer lifetimes L . The temperature of aging extended to the desired lifetime L is called the temperature index. For calculating a temperature index of general-purpose electrical machine insulation, the IEC recommends an upper service-life limit of 20 000 h = 20 kh. The resultant temperature index is labelled TI, the respective temperature T being written next to a slant line. If it turns out to be desirable to determine TI of a test material at L other than 20 kh, the appropriate value of L in kilohours is written in the notation.

Apart from determining the temperature index of a material, which is the simplest criterion of thermal endurance, the IEC method permits us to evaluate other features of thermal endurance. Thus the range (profile) of thermal endurance is an intercept of the graph $L/(1/T)$ between the points representative of $L = 20\,000$ h and $L = 5\,000$ h; while estimating the range of thermal endurance, a special method can be used to calculate lower 95-% confidence limits for the mean time of specimen aging at each temperature. The notation for a range of thermal endurance, RTE, includes the temperature indexes for 5 000 h and 20 000 h, separated by a slant line, and a lower 95-% confidence limit (in brackets) for a lifetime L of 5 000 h.

The most important thermal characteristics for a number of organic insulating materials such as plastics, petroleum oils, and waxes are the temperature of softening or flow point and fire point. These temperatures are basic parameters of thermal endurance of these materials.

Brittle materials and products such as porcelain or glass insulators are tested for resistance to thermal shocks, that is, to sharp temperature changes without impermissible impairment of basic properties.

Tests for cold endurance are important for insulating materials used in airborne electrical and radio equipment, outdoor electrical installations, and electrical units operating in cold premises.

9.2. Thermal Conductivity

Consider a specimen with an invariable cross section F and length h taken for the measurement of thermal conductivity. The opposite end faces of the specimen differ in tem-

perature. Assume the heat flux spreads lengthwise the specimen without going to its side walls and outwards. The equation for the steady process of heat transfer through a body showing a total thermal resistance, R_t , with a temperature difference (temperature gradient) between the hot and cold surfaces of ΔT , takes the form

$$P = \Delta T / R_t \quad (9.1)$$

where P is the power of thermal flux, that is, the quantity of heat passing across the body per unit time. This equation is analogous to Ohm's law for an electric circuit. Here P plays the role of current, and ΔT the role of potential difference. Measuring P in watts and ΔT in kelvins or degrees Celsius gives the unit kelvin per watt (K/W) for the quantity R_t . On the other hand,

$$R_t = \rho_{th} \frac{h}{F} \quad (9.2)$$

where ρ_{th} is the thermal specific resistance of a material; h is the length of path of thermal flow across the body; and F is the cross section of the body.

Formula (9.2) is analogous to the formula for electric resistance, where R_t acts as R , and ρ_{th} as ρ . Measuring R_t in kelvins per watt, h in meters, and F in square meters, we obtain the unit kelvin-meter per watt (K m/W) for the quantity ρ_{th} . The reciprocal quantity

$$\lambda = 1/\rho_{th} \quad (9.3)$$

which is similar to the electric volume conductivity of a material, is the thermal conductivity, or the coefficient of heat conduction. Its unit of measurement is the watt per meter-kelvin [W/(m K)] or the watt per meter-degree Celsius [W/(m °C)]. Obviously, $W/(m K) = W/(m °C)$.

Both relative and absolute methods are used for determining the thermal conductivity λ of various materials. A steady-state method measures λ in the steady process of heat transfer, and an unsteady-state method under unsteady thermal conditions. A relative steady-state method determines the temperature gradient between the end faces of a specimen with the heat flow set steady. The method may use a device shown in Fig. 9.1. A specimen 3 and reference material 5 of known thermal conductivity λ_{st} are placed between

a heater 2 (boiling water) with a temperature T_1 and a cooler 6 (melting ice) with a temperature T_3 . Both the specimen and the standard of reference are plates of the same cross section with thickness t and t_{st} pressed with a clamping board 7.

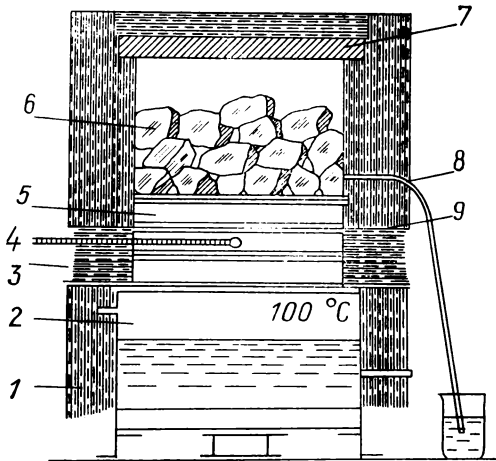


FIG. 9.1. Apparatus for determining thermal conductivity by a relative method

A metal spacer 9 secures good thermal contact between the specimen and the standard of reference and between the heater and cooler. The temperature T_2 of the spacer is measured with a thermometer 4. The device is enclosed in thermal insulation 1. Water is drained from the cooler through a tube 8.

At the steady state of thermal flow, in which case the temperature T_2 shown by the thermometer does not change with time, the powers of thermal flux, P and P_{st} , are the same both in the specimen and in the reference standard:

$$P = \frac{T_1 - T_2}{\rho_{th} \frac{t}{F}}, \quad P_{st} = \frac{T_2 - T_3}{\rho_{st} \frac{t_{st}}{F}} \quad (9.4)$$

Here t is the thickness of the specimen; t_{st} is the thickness of the standard of reference; F is the cross section of the specimen and standard; ρ_{th} and ρ_{st} are the specific thermal re-

sistances of the specimen and reference material respectively. Equating the right sides of Eq. (9.4) gives the expression for thermal conductivity in W/(m K):

$$\lambda = \lambda_{st} \frac{T_2 - T_3}{T_1 - T_2} \frac{t}{t_{st}} \quad (9.5)$$

The absolute steady-state measurement method (Fig. 9.2) consists in the following. A test specimen of thickness t ,

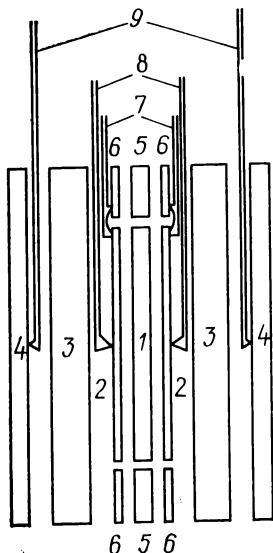


FIG. 9.2. Apparatus for determining thermal conductivity by an absolute method
1—electric heater element; 2—hot metal discs; 3—test specimens; 4—cooling discs; 5 and 6—guard rings of electric heater element and hot discs; 7—differential thermocouples to measure temperature difference between hot discs and guard rings; 8 and 9—thermocouples to measure T_1 and T_2

m, and cross-sectional area F , m^2 , is placed between a heater and cooler. The heater is commonly an electric heating element whose thermal power can be controlled by varying the applied voltage. The cooler is a hollow metal body through which cold water is passed. The temperatures of the hot and the cold surface, T_1 and T_2 , are recorded by means of thermocouples. As heat transfer becomes steady, in which state T_1 and T_2 remain invariable with time, the power of thermal flux, P , is found by measuring the electric power of the heater. The thermal conductivity is calculated by the formula

$$\lambda = \frac{Pt}{F(T_1 - T_2)} \quad (9.6)$$

Unsteady-state conductivity measurement methods rely on measuring the temperature gradient as a function of time under unsteady conditions of thermal flow. An advantage of these methods is a short time of measurement, merely a few minutes, against a few hours taken by the steady-state methods. In the test procedure, a specimen furnished with thermocouples is heated directly by an electric heater element or in an oven and the temperatures are noted. The thermal conductivity is then found using appropriate formulas. It is also possible to cool a preliminarily heated specimen and record time-dependent changes in temperature at various points on the specimen surface.

An unsteady-state method of measurement over a certain time-temperature range uses a test specimen in the form of a thin plate put on a heat absorber—a copper block surrounded on all sides with thermal insulation. A heater is placed on top of the specimen. The arrangement should ensure good thermal contact of the specimen both with the heater and with the heat absorber. The temperature difference between the heater and heat absorber is measured with a differential thermocouple, and the time-dependent readings are taken from a galvanometer connected in the thermocouple circuit (variations of U with time τ). Plotting τ as abscissas and $\log U$ as ordinates gives a linear decaying dependence $\log U$ (τ). The thermal conductivity is found by the formula

$$\lambda = \frac{CtM}{F(\tau_2 - \tau_1)} \log \frac{U_1}{U_2} \quad (9.7)$$

where C is the specific heat of copper, J/(kg K); M is the mass of the copper block, kg; t and F are the thickness, m, and cross section, m², of the specimen; U_1 and U_2 are galvanometer readings at the moments of time τ_1 and τ_2 (in seconds).

The method for measuring the thermal conductivity over a certain time-temperature interval sometimes uses a flat bicalorimeter consisting of two disc-type test specimens separated by a thin metal disc with a built-in thermocouple. The measuring unit is housed in a sealed box. The bicalorimeter is first heated and then placed in a chamber with an oil of definite temperature to let it cool down. The thermal conductivity is determined on the linear portion of the tem-

perature-time relation, that is, on the portion where the bicalorimeter cools at a regular rate. Knowing the temperatures of the specimens at the moments of time, τ_1 and τ_2 , and the values of specific heat for the specimens and the metal plate, we can find the thermal conductivity.

9.3. Softening Temperature and Flash Point

There are several methods for determining the softening point of a material. The "ring-and-ball" method is most popular (Fig. 9.3a). The device shown in the figure consists of

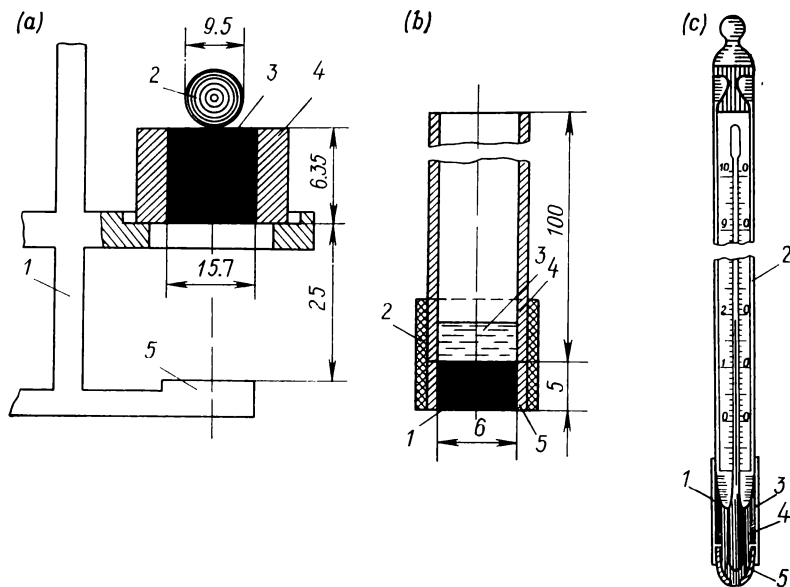


FIG. 9.3. Soft point measuring devices

(a) ring-and-ball tester; (b) tester using mercury; (c) drop-point tester

a brass ring 4 and a steel ball 2. The ring is filled up to the brim with a molten sample 3, the excess being cut off with a hot knife after sample cooling. The ball is then placed on the sample in the center of the ring. The rings with the samples prepared in this manner (the required number of sam-

ples being specified by the standard) are placed in a vessel containing water or glycerin (when testing high-melting materials) and set up on an upright 1. The vessel is heated at a rate of $5^{\circ}\text{C}/\text{min}$. The temperature is indicated by the thermometer whose bulb is located in close vicinity to the sample. The softening point is taken to be that temperature at which the ball squeezes out the material so that it touches a control plate 5 located at a certain distance from the lower edge of the brass ring.

It is more convenient to test some materials with a device shown in Fig. 9.3*b*. A glass tube 5 is placed on a glass plate rubbed with talc and filled to the brim with a molten sample 1. Next the glass tube 5 and glass tube 4 of the same diameter are butt joined together with a rubber sleeve coupling 2. Mercury 3 in an amount of 5 g is then poured into the tube 4 to form a mercury layer above the sample. The samples so prepared (as a rule four samples) are placed in a vessel with glycerin in the same manner as done in the "ring-and-ball method"; the lower edges of samples

must lie 50 mm above the level of glycerin and the upper ends of tubes 4 must be in the air above glycerin. The vessel is heated at a rate of $2^{\circ}\text{C}/\text{min}$. The softening point is assumed to be the temperature at which mercury presses out the sample and drops to the bottom.

Quite a number of organic materials are tested by the drop point measurement method. The tester shown in Fig. 9.3*c* is a thermometer 2 whose bulb is tightly fitted into a metal shell. Screwed on the shell is a metal tube 1 with a hole 3 to allow access for atmospheric air. A glass cup 5 filled with a sample is inserted in the tube until it bears up against pins 4. The excess of material poured into the cup is struck level with the brim and the material squeezed out by the thermometer bulb through the hole in the cup bottom is

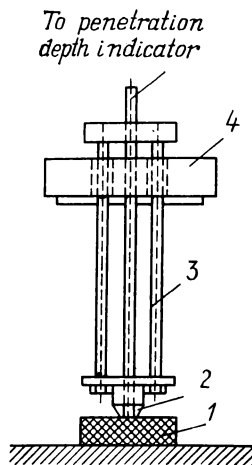


FIG. 9.4. Apparatus for testing plastics by Vicat's method

cut off with a knife. The device is placed into a test tube contained in a water or oil bath and heated at a rate of $1^{\circ}\text{C}/\text{min}$. The drop point is the temperature at which the first drop passes through the hole in the cup bottom and falls down.

Plastics are tested for softening temperature by Vicat's method both in the atmosphere (State Standard 15065-69) and in a liquid medium (State Standard 15088-69). This method of test is designed to determine the temperature at which a standard steel cylinder (indenter) penetrates into a test specimen to a specified depth under the action of a weight. In the tester shown in Fig. 9.4, an indenter 2 is fixed to a freely moving vertical rod 3 having a support for a changeable weight 4 chosen in accordance with the test specifications on the material in question. An indicator 5 with a scale division of 0.01 mm measures the depth of indentation and suitable instruments record both the indentation depth and the specimen temperature. The tester with a specimen 1 is placed in a chamber where the temperature is uniformly raised at a rate of $5^{\circ}\text{C}/\text{min}$ or $50^{\circ}\text{C}/\text{h}$. Petroleum oil, paraffin, glycerin, and silicone grease may serve as a liquid medium; the liquid chosen must be chemically inert to the specimen. The temperature at which the indenter has penetrated into the specimen body to a depth of 1 mm is taken as the point of softening.

The Martens method for determining the temperature of softening is suitable for plastics and other similar materials. The test specimen 9 of definite cross section and length (State Standard 21341-75) is clamped with its one end in a grip 10 made fast to a support 11, the other end of the specimen being secured in an upper grip 8 rigidly attached to a bar 7 along which a weight 6 can be shifted. The entire test unit complete as a rule with three pairs of grips for testing three specimens at a time is placed in a chamber 1. The temperature in the chamber is measured with a thermometer 5 whose bulb is located close to specimens. Fixed to the end of a bar 7, a certain distance away from the specimen axis, is a light rod 2 with a pointer 3 that slides alongside a scale 4 marked in millimeters. The weight 6 shall occupy such a position on the bar as to produce a bending stress of 5 MPa on a 100-mm long specimen portion between the grips.

For this purpose one must calculate a distance l (cm) from the center of gravity of the weight G to the specimen axis:

$$l = \frac{50W - 12g}{G} \quad (9.8)$$

where W is the moment of resistance of the specimen, cm^3 ; g is the mass of the bar proper, kg; and G is the mass of the weight, kg.

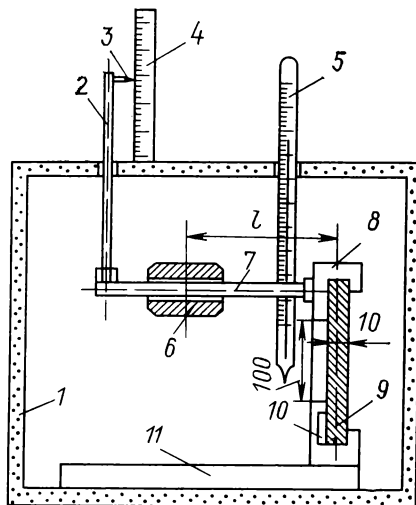


FIG. 9.5. Martens apparatus

Noting the position of the pointer 3 on the scale with the specimen under load at normal temperature, it is now necessary to raise the temperature in the chamber at a rate of $50^\circ\text{C}/\text{h}$. The temperature at which the pointer shifts 6 mm down from the initial position (or the temperature at which the specimen breaks up) is the softening point (Martens heat stability). A specimen from plastics, ebonite, and other materials has a height of 1 cm and width of 1.5 cm (this size is at a right angle to the drawing plane in Fig. 9.5). When fixed as shown in the figure, the specimen's moment of resistance is

$$W = \frac{ab^2}{6} = \frac{1.5 \times 1}{6} = 0.25 \text{ cm}^3 \quad (9.9)$$

where a and b are the width and height of the specimen respectively. With the mass of weight g equal to 0.65 kg, l ranges between 15 and 16 cm.

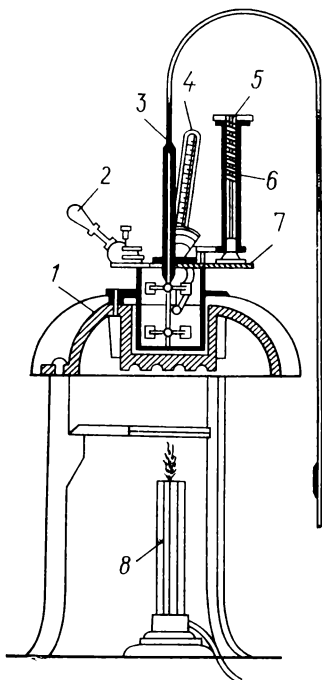


FIG. 9.6. Martens-Pensky apparatus for determining the flash point of petroleum products

Obviously, all the deformation-temperature measurement methods considered above are conditional to a large measure because the character and the value of mechanical stress and also the value of critical deformation are in essence chosen at will. The same also concerns the rate of heating; the matter is that the deformation of amorphous substances heavily depends on the time of action of the applied load.

For crystalline dielectrics (such as waxes), a better criterion is the melting point. The measurement methods suitable for the purpose are the method of clarification of a capillary tube, the Zhukov method (State Standard 4255-75) and others. Since crystalline substances show quite a definite temperature of melting, these methods give fairly reliable results.

The flash point of a material is the temperature at which the vapors of the liquid under test or molten organic substance form a mixture with the air, which flares up when it comes in contact with a source of ignition (a gas burner, for example). Heating the substance further on after determining the flash point causes the sample to catch fire from the open flame brought up to it. The temperature at which a substance inflames and continues burning for at least 5 s after removal of the burner flame is the fire point, or burning point, of the substance under test.

An apparatus with an open test tank (State Standard 13921-68) makes a suitable device for determining the flash and fire temperatures. The Martens-Pensky apparatus with a closed test tank is most popular for testing organic substances, mainly petroleum products (Fig. 9.6). The device comprises a metal test tank with a double cover 7, the lower being stationary and the upper movable in both directions to a definite angle. Both covers have holes which can or cannot register with each other depending on the position of the upper cover. A tube 6 with a rod inserted into it is fixed to the cover. On rotating a head 5 of the rod, the movable cover begins to turn, thereby bringing the holes into coincidence. At the same time, a small burner 2 with a flame set at 3 or 4 mm in height is brought up to the open surface of oil under test. On releasing the head 5, the movable cover will take up the initial position. The stationary cover has a clamping device to fasten a thermometer 4. The shaft of a paddle 3 passes through a hole in the center of the cover 7. The paddle consists of two pairs of blades, the lower pair being immersed in oil and the upper positioned above the surface of oil. The apparatus is placed in a metal case 1 with a burner 8.

After filling the test tank with the liquid under test to a certain mark, and setting the cover 7 with the requisite accessories in place, heating is started while stirring the liquid and the air above its surface with the paddle 3. The rate of heating shall be 1°C/min if the sample is expected to have a fire point below 50°C; 5 to 8°C/min if the sample is expected to have a fire point from 50 to 150°C and then 2°C/min 30°C before the expected ignition; 10 to 12°C/min if the sample is likely to have a flash point above 150°C and then 2°C/min 30°C before the expected ignition.

As the temperature approaches the point at which the ignition is likely to occur, the sample is tested for inflammation at every degree of temperature rise. For this the stirring is terminated, the movable cover is turned by rotating the head 5 to open the holes, and the flame is brought in contact with the surface of oil. The temperature of oil is noted when a blue flame appears at the oil surface for the first time. The flash temperature so found shall be corrected to allow

for an error ΔT due an atmospheric pressure:

$$\Delta T = 0.91 (0.1 - p) (273 + T) \quad (9.10)$$

where p is the atmospheric pressure, MPa; and T is the measured flash point, °C.

Before testing, the apparatus shall be thoroughly cleaned and dried. This is especially the case if the test tank is washed with gasoline because even a minute quantity of gasoline in oil greatly decreases its flash point.

9.4. Accelerated Tests for Thermal Endurance

These tests involve exposure of organic materials and products to the destructive effect of increased temperatures, for which reason they are often called thermal aging tests. The test procedure consists in measuring the most important electrophysical characteristics of a material that experiences the aging effect of high temperatures. The test data give evidence to changes in the mass, mechanical strength, elasticity, electrical parameters, and other properties of the material.

A sharp decrease in elasticity of a number of organic materials under the effect of thermal aging often proves an acceptable criterion of thermal endurance. This decrease in elasticity and attendant brittleness usually show up much earlier than deterioration of electroinsulating properties. To reveal more clearly the process of aging, it is sometimes expedient to moisten the specimen after exposure to elevated temperatures. In testing vanishes and resins for thermal endurance under accelerated conditions, mechanical properties generally prove more liable to deterioration than electrical properties.

There are also other criteria of thermal endurance for electrical insulating materials. Thus, for varnish films (State Standard 13526-68), the criterion is one of the parameters, thermal elasticity or thermal stability. The first parameter is the time of heating of a varnish film at a definite temperature following which the film develops cracks when subjected to bending or stretching. The second parameter is the time of heating that causes an inadmissible loss in mass of the film.

Other conditions being the same, the rate of changes in the electrophysical characteristics of a material greatly rises with an increase in the temperature of aging. These changes obey the general regularities of changes in the rate of chemical reactions as a function of temperature. The time of aging, L , is related to the temperature of aging, T_a (K), through the expression

$$\ln L = \frac{A}{T_a} + B \quad (9.11)$$

where A and B are constants for the material tested under given conditions. So, the plot of the logarithm of L against the reciprocal of the temperature of aging must appear as a straight line. In most cases, the slope of these straight lines is such that a decrease in the time of aging by one half corresponds to an increase in the temperature of aging by 8 to 12° (the rule of "ten degrees").

It should be remembered that the rate of aging of solid organic insulation strongly depends on its thickness. With an increase in the thickness of insulation, it is more difficult for oxygen to penetrate deep into the bulk of a material; the process of aging may slow down to such an extent that a thicker insulation will show the properties corresponding to the next higher class of thermal endurance as against the properties of a thinner insulation prepared from the same material.

Aging tests would require many months and even years should they be conducted under natural conditions of service. That is why it is an established practice to employ accelerated methods of testing at temperatures and voltages which considerably exceed the operating parameters. Test methods use thermal humidity cabinets similar to the ones described above.

The test data so obtained permit us to estimate the life of insulation at elevated temperatures by using Eq. (9.11) and plotting the graphs which relate the log of life time L to $1/T_a$. By extrapolating the plots, it is possible to determine the life of insulation at operating temperatures.

Thus, for oil-impregnated paper we can plot the graph relating the temperature to the time required for the mecha-

nical strength of paper to decrease to a set value (commonly to 70% of the initial strength), or the graph showing the relation between the temperature and the time it takes 1 g paper to evolve 0.1 cm³ CO and CO₂. The plot of temperature *versus* time taken for enameled wire insulation to break down has a similar form.

Apart from testing at increased temperatures and/or voltages, specimens are subjected to the effect of low temperatures, moisture, vibration, and impacts. The test conditions are repeated in the specified sequence. At intervals between these types of test the specimens are checked for $\tan \delta$ at the preset test voltage under ordinary temperature conditions. These test conditions make up in combination a test cycle. It is common to test a specimen under the conditions at which the specimen fails after approximately 10 test cycles.

A test cycle may include the following test procedures or some of them: (a) sharp heating to the preset temperature; (b) holding at that temperature; (c) sharp cooling to the preset temperature; (d) vibration and mechanical impacts; (e) exposure to a humid atmosphere; (f) transition to room temperature; (g) holding at room temperature; (h) electrical testing for determining $\tan \delta$ at the specified test voltage, and other electrical parameters.

In a number of cases it proves sufficient to hold the specimen at an increased temperature and simultaneously subject it to a test voltage 5 to 10 times in excess of the operating voltage. The higher the test voltage and temperature, the faster the specimen breaks down.

Practice shows that for the accelerated aging tests to give reliable results, it is necessary, first, to expose a specimen to a temperature which is not so high as to cause its failure earlier than in the 50-h period, second, to test the specimen at three or four various temperatures, and, third, to obtain the test data not later than 1 000 h after exposure to the lowest temperatures.

Thermal aging tests of heterogeneous materials, such as insulating compounds widely used in electrical machines, require a large number of specimens because of a considerable scatter in the test results. As least 25 specimens should be tested at each temperature to obtain the reliable results. If it is necessary to extend the results of tests made on small

specimens in order to apply them to a large area of insulation, one should introduce corrections for the increase in the area.

9.5. Thermal Shock Resistance

This characteristic is important for brittle materials and components. The stability of a material to thermal shocks depends on its temperature coefficient of length, for which reason we may use a ratio A/α_l as a tentative estimate of this parameter. In this ratio, A is a coefficient that takes into account the mechanical strength and thermal conductivity of a material and α_l is the TC of length. If a material is heterogeneous and has surface defects (scratches and cracks), its endurance against thermal shocks strongly decreases, which is quite explicable on the basis of the theory of strength of a brittle body. Some materials, such as glass, are subjected to etching by hydrofluoric acid to make them more resistant to thermal shocks; hardening produces the same effect.

Porcelain pieces are tested for thermal shock resistance in accordance with the test procedure specified by State Standard 5862-79 E. They must withstand three cycles of heating and cooling without the signs of deterioration of basic properties. Depending on the type of porcelain piece, the temperature of heating may range from 40 to 80°C; the time of heating varies with the mass of a piece, but must not exceed 60 min. Hot insulators are quickly immersed into ice water and held there for a time period t . After three cycles of thermal shocks, the cooled and fully dried insulator is inspected and then subjected to high-voltage tests.

9.6. Cold Resistance

As the temperature falls below the normal, materials not only show stability in electroinsulating properties, but rather have a tendency toward improvement of these properties. The mechanical properties of materials, however, change drastically at low temperatures; materials degrade in elasticity and flexibility and become more brittle. It is not in-

frequent that compounds, resins, and similar materials develop cracks on cooling.

Most of the cold resistance test units rely on the direct testing of materials for mechanical properties at low temperatures and on the comparison of these properties with the properties at normal temperature. The method of deformation (tension) at low temperatures is applicable to elastic materials for determining the coefficient of cold resistance (frost resistance):

$$K = l_f/l \quad (9.12)$$

where l_f is an elongation of the working portion of the specimen at low temperature, mm; and l is an elongation, mm, under the same tensile force but at normal temperature.

The specimens used for determining the coefficient of cold resistance are in the form of a plate or blade 25 mm in length (of the working portion), 6.4 mm in width (or 3.2 mm for more rigid materials) and 1 or 2 mm in thickness. The test units employed are similar to the one shown in Fig. 9.7a. The apparatus has a thermally insulated metal cup *11* or, sometimes, a Dewar flask instead of the metal cup. The test specimen clamped in grips is lowered by a wire rope into a cup *3* and turned so that the lower grip shoulders bear against the cup's internal lugs. The space between the cups *3* and *11* is filled with a cooling medium—a mixture of ethyl alcohol with dry ice.

The process of testing consists in determining the elongation of the specimen both at normal and at low temperatures, the tensile load being the same. The tensile load and temperature of the cooling medium are prescribed in test specifications. The specimen undergoes deformation under the action of weights placed on the support; the force is transmitted to the specimen along the rope passed over a block. The specimen elongation is read from the scale marked on the rod fastened on a bracket, so the instrument readings do not change as the bracket moves up and down. Preliminary calibration of the instrument should ascertain a correction for rope elongation.

An advantage of the apparatus lies in the absence of contact of the specimen with the cooling medium which could cause swelling of the material.

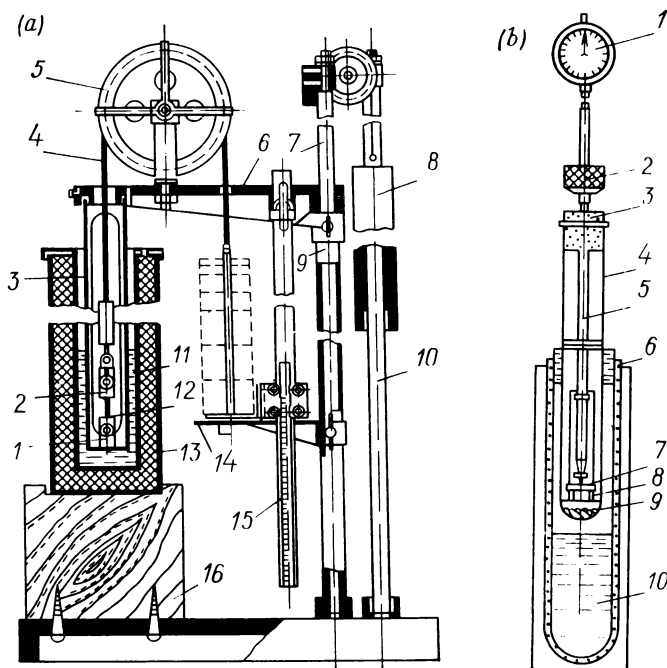


FIG. 9.7. Cold-resistance measuring devices

(a) device based on measuring deformation in tension; 1 and 2—grips; 3—cup with internal lugs; 4—rope; 5—block; 6—bracket; 7—guide column; 8—balance weight; 9—tube; 10—guide column for balance weight; 11—metal cup; 12—specimen; 13—thermal insulation; 14—support for weight; 15—scale; 16—pedestal
(b) device based on measuring deformation in bending; 1—micrometer; 2—weight; 3—plug; 4—glass tube; 5—quartz tube with ebonite tip; 6—vessel with cooling mixture; 7—specimen; 8—supports; 9—spherical base; 10—cooling mixture

Cold resistance is also estimated by the method of low deformation in bending. The method uses a test apparatus shown in Fig. 9.7b. The test specimen placed on two supports undergoes flexural strain due to the action of a weight-loaded quartz tube with an ebonite tip. A pointer micrometer indicates the sag caused by the weight. The lower part of the apparatus is inserted into a glass tube housed in a thermally insulated vessel with a cooling medium. The specimen is allowed to freeze in the loaded state. When the specimen temperature reaches the desired limit, say, minus 70°C,

the apparatus with the glass tube is raised and fixed at a certain height above the level of the cooling mixture. Next the weight is applied and the readings are taken from the thermometer and the pointer micrometer which indicates the growing strain on the specimen being heated. The measure of cold resistance here is the temperature at which the specimen deformation reaches 1 mm. The weight 2 is chosen so that the sag of the specimen can come to approximately 1 mm at normal temperature. After freezing of the specimen, the load is increased 2 or 3 times depending on the specified conditions of test and the specimen deformation is noted during its slow defrosting. Quartz glass is taken as a material of the tube 5 for its rather small temperature coefficient of thermal expansion. Cold resistance is sometimes determined from changes in the modulus of elasticity at small deformations under low temperature conditions.

PHYSICOCHEMICAL CHARACTERISTICS

10.1. General

Apart from the characteristics discussed above, of much practical significance are various general physical and chemical characteristics of electrical insulating materials. These characteristics help evaluate the quality of materials and thus assign each the function it must serve to the best advantage.

Among a variety of the physicochemical characteristics, it is practically important to know some of these, depending on the kind of material and its field of application. To most widespread characteristics of this type belong the acid number and viscosity of insulating liquids and substances prone to softening, chemical stability of materials to corrosive media, moisture resistance and atmospheric durability of materials exposed to climatic influences.

10.2. Acid Number

Aging of insulating liquids entails irreversible physicochemical changes and evolution of chemical compounds, in particular acidic compounds. One of the basic characteristics by which it is possible to judge of the degree of aging of a mineral (petroleum) oil, is the acid number.

The acid number k is the number of milligrams of potassium hydroxide, KOH, required to neutralize all the acidic compounds entering into the composition of 1 g of oil. The procedure of acid value determination is as follows. Add 4 or 5 drops of an alkali indicator (as a nitroso yellow) in a flask with an alcohol. Warm the flask and neutralize the alcohol, while thoroughly agitating it, with alcoholic 0.05N KOH (a normal alcoholic solution of KOH). Stop

neutralizing the alcohol as soon as its color changes from the yellow to the green. Next pour the hot neutralized alcohol out of the flask into another flask containing 10 g of the test oil. Warm the mixture and leave it to boil for 5 min.

Now add 4 or 5 drops of the alkali indicator to the hot mixture, and, using a buret, introduce in drops alcoholic 0.05N KOH into the mixture until it turns from yellow to green. This process is known as titration. The amount of KOH added to the mixture is determined from the buret scale.

Alcoholic KOH of the above concentration is often replaced by a suitable reagent. The acid value k , expressed as the number of milligrams of KOH per gram of the oil tested, is calculated by the formula

$$k = VT/m \quad (10.1)$$

where V is the volume of alcoholic 0.05N KOH used for titrating the mixture, ml; T is the titration standard of 0.05N alcoholic potash expressed in milligrams of KOH; and m is the sample of oil, g. The permissible value of k is given in the specifications on a material. Thus, for transformer oil of selective purification (State Standard 10121-76), the acid number shall not exceed 0.02 mg KOH per 1 g oil.

10.3. Chemical Resistance

The chemical resistance of insulating materials has particular importance wherever insulation has to operate in the atmosphere laden with chemical substances or in direct contact with chemicals, chemical solutions, and vapors. Solid insulating materials used in oil-filled transformers, capacitors, and other electrical apparatus must resist the attack of petroleum oil. Insulation impregnated or coated with varnishes and enamels must show good stability and resistance to attack by oils and solvents contained in the impregnants. Insulation of shipborne electrical equipment must not deteriorate under prolonged exposure to the humid air saturated with sea salts. The above examples attest to the need of determining the chemical resistance of materials. The methods of estimating the stability of plastics to the

corrosive effect of chemical media are set forth in State Standard 12020-72. The standard does not cover foam and porous materials. The chemical stability of a plastic material is evaluated by changes in the mass, linear dimensions, and mechanical properties of standard specimens in the stress-free state, and also by the tendency to splitting in the stress-strain state after the specimens have been exposed to reagents for a definite length of time. Test specifications describe in more detail the procedure of testing a particular plastic material for chemical resistance. They prescribe the procedure of conditioning a specimen for testing purposes, concentration of reagents, time and temperature of testing, apparatus, and instruments. The reagents (in percent concentration) recommended for testing plastics for chemical resistance are the following:

Acids:

sulfuric (1.84 g/cm ³)	3, 30, 100
nitric (1.41 g/cm ³)	10, 40, 100
hydrochloric (1.19 g/cm ³)	10, 100
chromic	40
acetic	5, 100
citric	10
Sodium hydroxide	1, 10, 60
Sodium chloride	3, 10]
Sodium hypochlorite	10
Sodium carbonate	2, 20
Ammonium hydroxide (0.9 g/cm ³)	—
Hydrogen peroxide	3, 30
Ethyl alcohol	50, 96
Phenol	5

Other reagents used in testing plastics for chemical resistance include oleic acid, acetone, methyl alcohol, dichloroethane, carbon tetrachloride, heptane, benzene, toluene, aniline, mineral oil, transformer oil, olive oil, kerosene, gasoline, turpentine, 1-% soap solution, and other substances.

Determining chemical resistance by changes in mass.
The method of test covers the procedure for determining changes in the mass of a test specimen on exposure to a cho-

sen reagent at temperatures of 20°C, 40°C, 60°C, 80°C, 100°C, 125°C and then at an interval of 25°C. The test duration depends on the time required for plastic specimens to attain sorption equilibrium or to lose stability in the test medium. The specimens are weighed after 12 h, 24 h, 36 h, 48 h, 72 h, 96 h, 120 h, and then every 7 days. The specimen that has passed the test may either lose or gain in mass. The chemical resistance of the material is evaluated by the averaged change in the mass of several specimens.

The test specimens for molded or extruded plastics shall be in the form of a disc 50 mm in diameter and 3 mm in thickness. The specimens are cut from laminated or sheet plastics and the end faces of laminated specimens are coated with the same binder as used in the production of the material in question. The specimens for thinner materials are also cut in the form of a disc 50 mm in diameter. The test specimen for rods shall be 50 mm in length and not over 50 mm in diameter. The test specimen for tubes shall be 50 mm in length and not over 50 mm in diameter. At least 5 specimens shall be tested. Specimens are conditioned prior to test as specified by the standard on a material (for example, State Standard 12423-66).

A reagent is taken in an amount of 8 ml per 1 cm² of the surface of the test specimen for plastics free from extractable substances. In testing plastics showing a tendency to dissolve or the ones containing extractable substances, a reagent shall be taken in an amount of 20 ml per 1 cm² of the entire surface of a test specimen.

After loading the specimens in a bath, the reagent shall be mixed or stirred not rarer than once a day. Every seven days, the specimens shall be removed from the reagent one at a time, washed, wiped dry, and weighed. A percentage increase or decrease in the mass of a specimen is determined as follows

$$\Delta M = \frac{(M_1 - M) 100}{M} \quad (10.2)$$

where M and M_1 are the mass of the specimen before and after holding in the bath.

To find the quantity of a substance extracted from a specimen under the action of a reagent, one should dry first

the specimen at 50°C in a vacuum to a constant mass, then recondition it and weigh. The amount of an extractable substance in percent is

$$\Delta M_1 = \frac{(M - M_2) 100}{M} \quad (10.3)$$

where M_2 is the mass of the specimen after its drying and reconditioning. Specimens shall be weighed accurate to within 0.1%.

Determining chemical resistance by changes in linear dimensions. The method of test determines changes in the linear dimensions of specimens after prolonged exposure to a reagent. The form, size, and number of specimens, and also the quantity of reagent remain the same as in the above method. Before testing, the thickness in the central portion of the disc and two mutually perpendicular diameters of each specimen are measured, the places of measurement being marked, following which the specimens are placed in the bath with a reagent. Every 7 days the specimens are taken off the bath, washed, wiped with a cloth, and checked for dimensions at the same places. A change in any of the linear dimensions in percent is

$$\Delta l = \frac{(l_1 - l) 100}{l} \quad (10.4)$$

where l and l_1 are linear dimensions of the specimen before the first immersion into the reagent and after exposure to the reagent.

The degree of stability of the linear dimensions of a specimen to the effect of a chemical reagent is a criterion of the possible use of plastics for the manufacture of products, the basic requirement for which lies in retaining the shape on exposure to chemical substances.

Determining chemical resistance by changes in mechanical properties. The method of test determines the stability of the mechanical properties of plastics under prolonged exposure to chemical reagents. The form, dimensions, and number of specimens for plastic materials are chosen in compliance with the standards. After exposure to a reagent, the specimens are washed, wiped, and tested for one or two most important characteristics such as the tensile strength, static flexural strength, impact bending strength, hardness,

percentage elongation at rupture, and mechanical stress in bending that causes a deflection equal to 1.5-fold thickness of the specimen. Mechanical tests are run as prescribed by standards. Relative changes in the mechanical parameters may serve as the basis for dividing plastics into three groups as regards the stability of their mechanical properties (Table 10.1).

TABLE 10.1

Stability of the Characteristics of Plastics on Exposure to Reagents

Type of plastic	Relative changes in mechanical characteristics, %		Stability
	Strength properties	Deformation	
Thermoplasts	0-10	0-10	Good
	10.1-15	10.1-20	Adequate
	over 15	over 20	Poor
Thermosets	0-15		Good
	15.1-25	—	Adequate
	over 25		Poor

As noted earlier, the standard on a material specifies the kind of reagent, test duration, and, sometimes, the additional characteristics to be determined during the test.

Thus, State Standard 2718-74 prescribes the following test procedure for a type III pertinax (shipborne insulation). The specimens provided with tightly fitted electrodes for the measurement of the insulation resistance R (see Sec. 1.2) are immersed into a 3-% sodium chloride and left to stand for 24 h at 20°C. After the measurement of R , which shall be not less than $5 \times 10^7 \Omega$ for this grade of pertinax, the specimens are withdrawn from the solution, thoroughly washed with drinkable water, wiped dry with filter paper, and allowed to stay in the air for 1 h at 20°. The specimens are then checked for other properties if necessary.

Electrical insulating pertinax designed for work at 50 Hz is also tested for oil resistance. The specimens shaped like

a 100 by 100 mm plate of thickness S are immersed in transformer oil preliminarily heated to 70°C . The transformer oil is then heated to 105°C (for pertinax grades I, II, III) or to 130°C (for grades IV and V) during 40 to 90 min and then left to stand for 4 h. The specimens removed from the oil shall be free from bubbles and swelling. The end faces may develop thread-like cracks.

In testing materials for chemical resistance, it is necessary to secure the worker's safety and strictly observe the instructions on safety engineering and labor protection.

The basic means of individual protection against corrosive media are gloves from a 0.7-mm thick synthetic resin such as nairit latex (chloroprene rubber) amenable to ready deactivation. An organic glass shield with a rubber band loop effectively protects the face and eyes from sprays of chemically active substances. Tests should be run in exhaust cabinets or special boxes turned out by the industry as complete sets.

10.4. Viscosity

This is an important characteristic for evaluating the working and technological properties of many materials.

The viscosity of transformer oil is closely related to its cooling capacity. Also, the effectiveness of the production processes intended for the manufacture of various materials greatly depends on the viscosity of ingredients such as oils, varnishes and compounds which serve as impregnants of cable and capacitor insulation, paper and cloth (for the production of varnished paper, varnished cloth, plastic laminates) and also as adhesives for micanites and as coatings for wire and sheet steel. There are basically a few kinds of viscosity: dynamic, kinematic, and relative viscosity, the last being determined by simplified and conditional methods.

The unit of dynamic viscosity is the pascal-second (Pa s). The pascal-second is that dynamic viscosity of a medium at which the two layers 1 m distant from each other in the direction perpendicular to the laminar stream show a difference in flow rates of 1 m/s due to the action of a shearing

stress of 1 Pa. Another unit of viscosity that still finds use in practice is the poise equal to 0.1 Pa s.

The methods for determining the dynamic viscosity of liquids rely on Stokes's law or Poiseuille's law.

By Stokes's law, the speed v (m/s) of a solid sphere of radius r (m) moving in an unlimited liquid medium of dynamic viscosity η (Pa s) under the continuous action of force f (N) is equal to

$$v = \frac{f}{6\pi r\eta} \quad (10.5)$$

By Poiseuille's law, the quantity of liquid, Q , with a dynamic viscosity η that flows under the action of small pressure p for a length of time, t , through a capillary of length l and radius r (at $l \gg r$) is found by the formula

$$Q = \frac{\pi}{8} \frac{pr^4}{l\eta} t \quad (10.6)$$

The kinematic viscosity ν (m²/s) is the ratio of the dynamic viscosity of a liquid, η (Pa s), to its density ρ (kg/m³):

$$\nu = \eta/\rho \quad (10.7)$$

In other words, m²/s is the kinematic viscosity of a medium of a density of 1 kg/m³, the dynamic viscosity of which is equal to 1 Pa s. In practice, the kinematic viscosity is still measured in stokes (St); 1 St = 10⁻⁴ m²/s. The kinematic viscosity of water at 20°C is equal to approximately 1 cSt (one hundredth of the stoke); at 20°C, the dynamic viscosity of water is equal to about one centipoise (0.001 Pa s) and its density to 1 kg/m³.

Relative viscosity is a characteristic obtained at a definite technique of testing. This quantity is related to dynamic and kinematic viscosities through approximate empirical formulas. Such methods are less accurate than those described above, yet they still find wide application, though the scope of uses is rapidly diminishing. The viscosity of all liquids, providing they do not undergo chemical transformations in heating, decreases rather heavily with increasing temperature. While testing a liquid for viscosity, we thus must know for certain the specified temperature of the sample during measurements. Test apparatus are as a rule furnished with a water tank or other suitable arrangements

to heat the test liquid and keep its temperature at the desired level.

The viscosity of liquids is measured with viscometers. Depending on its design, the device can measure either the relative or the dynamic viscosity, or can give directly the values of kinematic viscosity.

Ball viscometers measure the speed of a steel ball with which it sinks into the test liquid under its own weight. Using a stopwatch we can note the time during which the ball travels a certain path along the vertical between the two marks drawn on the wall of a measuring glass cylinder with the liquid under test. The lower the viscosity of a liquid, the smaller should be the ball so that its speed of submersion cannot be too high but adequate enough to measure it to a set accuracy. The dynamic viscosity of a liquid is calculated with formula (10.5); for this, we should measure v and r directly and substitute the weight of a ball for f , decreasing therewith the ball mass by the mass of a liquid in the volume that equals the ball volume (according to Archimedes' principle). As mentioned above, formula (10.5) applies to a ball moving in an unlimited medium. In order to allow for the effect of the walls and bottom of a vessel, the value of η found from this formula should be divided by a correction factor

$$k = \left(1 + 2.4 \frac{r}{R}\right) \left(1 + 3.1 \frac{r}{L}\right) \quad (10.8)$$

where r is the ball radius; R is the vessel radius; and L is the vessel height. The ball viscometer gives accurate results of measurement corrected for the wall effect if r/R is less than 0.1 and the ball covers the distance that does not exceed half the vessel height. In testing a nontransparent liquid, the motion of a ball can be detected by X-raying the liquid or using electric contacts being closed by the ball.

Rotary viscometers determine the viscosity of a liquid from the power expended on rotating a cylinder in the test liquid or from a degree of deceleration of the rotary cylinder after switching off the motor. In its simplest design, the rotary viscometer consists of two coaxial cylinders, an external stationary and an internal rotary cylinder, the liquid under test being filled in the space between the cylin-

ders. The internal cylinder can rotate about its vertical axis under the action of a certain force, say, the action of a weight suspended by a rope that passes over a block fitted on the shaft of the rotary cylinder. The dynamic viscosity of a liquid is determined by the formula

$$\eta = k \frac{P - \Delta P}{n} \quad (10.9)$$

where P is the device weight; ΔP is a correction for friction of the device bearings; n is the rotational speed of the internal cylinder; and k is a constant dependent on the device dimensions.

Rotary viscometers are rather convenient for testing high-viscosity liquids such as oils at low temperatures, molten bitumens, greases of various suspensions, and other viscous materials. A viscometer properly modified in design can combine the measurement of the viscosity of a liquid with the measurement of its electric resistivity in terms of the leakage current through the cylinders. Such measurements permit studying the relation between the conductance and viscosity for such materials as molten glasses, resins, and others. There are devices, such as a ПБП-1 type plastometer-viscometer (State Standard 9127-59), that combine the measurements of viscosity with ultimate strength measurements.

Electric motor-driven viscometers, type ЭВП, can indicate viscosity directly on the scale of an instrument mounted on the control desk. The device of this type operates in the following manner. A cylindrical extension piece of radius R and height H fastened to a vertical shaft is immersed into a test liquid and set in rotary motion by a fractional horsepower motor suitably connected with measuring circuit. Extensions are changeable to enable testing substances that widely differ in viscosity. The dynamic viscosity is found by the formula

$$\eta = \frac{M}{4\pi R^2 H \omega} \quad (10.10)$$

where M is the micromotor torque; and ω is the angular speed. This formula holds true if the extension rotates in a vessel with a diameter $D \geq 2R$.

Universal (Engler) viscometers determine the viscosity in terms of the time it takes a definite amount of liquid to flow out through a tube of a standard diameter. Such a viscometer can measure the viscosity of a liquid in degrees of rela-

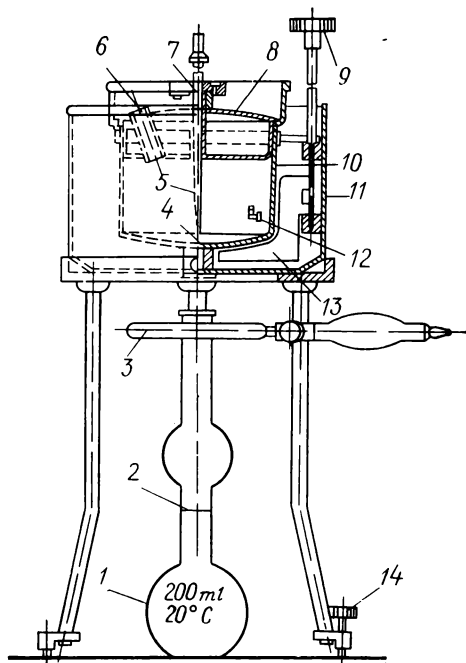


FIG. 10.1. Engler viscometer. Schematic

tive viscosity (in Engler degrees, for example). A test liquid is poured into an inside-gilded brass cup 10 with the internal diameter of its main portion (below its expanded portion) equal to 106 mm (Fig. 10.1). The cup is housed in a vessel 11 to provide for a water or oil bath. The cup cover 8 has an orifice 6 for a thermometer to measure the temperature of a liquid and a hole 7 for a tapered peg 5 that closes an inlet 4 into a vertical stainless steel or platinum nozzle having the shape of a cylindrical polished channel 2.8 mm in diameter and 20 mm in height. The amount of liquid poured into the

cup 10 should be such that it be level and come in touch with three pointed pieces 12 simultaneously. This also helps check at the same time the device for horizontal positioning. The device can be adjusted for proper position, if need be, with set screws 14 on its feet. The height of the pointed pieces above the lower orifice of the nozzle is 52 mm. The liquid in the vessel 11 is stirred with a mixer 13 put in motion by means of a knob 9 and heated with a circular gas burner 3 or electric heater (it is also possible to pour into the vessel just hot water, thus dispensing with a heater). The temperature is measured with a special thermometer clamped in a grip. Placed under the viscometer nozzle is a volumetric flask 1 whose neck bears a mark 2 indicating that the flask contains 200 ml of a liquid.

The test procedure reduces to the following. Heat the liquid in the cup 10 to the desired temperature and keep it steady. Take off the peg 5 and, at the same time, set the stopwatch going. Note the time the liquid takes to fill the flask to the mark, disregarding the height of foam. Dividing the time of outflow of 200 ml of the liquid at the test temperature by the constant of the device gives the desired relative (Engler) viscosity (RV) in Engler degrees.

The constant (water number) of a universal viscometer is the time required for 200 ml distilled water kept at 20°C to flow out from the device cup; the constant lies in the range from 50 to 52 s.

Capillary (Ostwald) viscometers measure the kinematic viscosity of, say, petroleum products (State Standard 33-66).

Capillary glass-tube viscometers are available in several types (State Standard 10028-67).

A type ВПЖ-1 viscometer (Fig. 10.2a) is designed to measure the viscosity of transparent liquids at positive temperatures. A ВПЖ-2 viscometer (Fig. 10.2b) and a Pinkevich viscometer measure the viscosity of transparent liquids both at positive and at negative temperatures. Test methods make use of constant-temperature cabinets that maintain the desired test temperature invariable over a wide temperature range from minus 60 to plus 150°C. The error in the measurement of temperature should lie within $\pm 0.1^\circ\text{C}$ at T ranging from minus 30°C to plus 150°C and within $\pm 0.25^\circ\text{C}$ for a temperature range from minus 60°C to minus 30°C.

A constant-temperature cabinet is filled with one of the following thermostatic liquids: industrial (hydrolytic) ethyl alcohol or synthetic ethanol and industrial isooctane to maintain temperatures from minus 60 to 0°C; distilled water to keep temperatures in the range from 0 to plus 90°C;

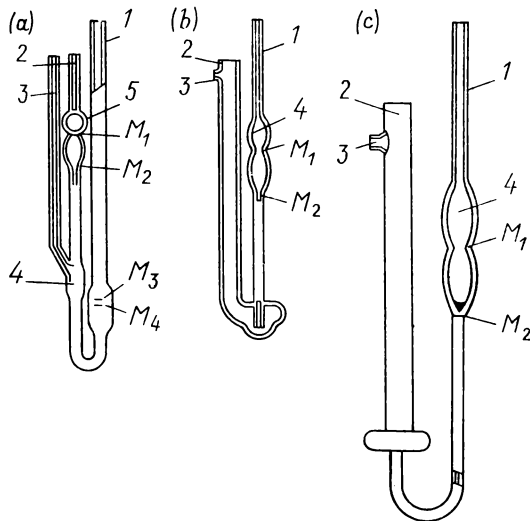


FIG. 10.2. Capillary viscometers

(a) БИИК-1 type for testing transparent liquids at positive temperature; (b) БИИК-2 type for testing transparent liquids at negative and positive temperatures; (c) Pinkevich viscometer

undiluted glycerine or glycerine diluted with water in the proportion 1 to 1, light petroleum oil, and 25-% aqueous solution of ammonium nitrate for holding temperatures above plus 90°C.

Ice, dry ice, and liquid nitrogen can be used for cooling liquids in a constant-temperature chamber.

When no special thermostat is available, the viscosity of liquids at plus 15°C may be determined with a Dewar flask and a test tube about 65 mm in diameter with a viscometer inserted into it. The test tube complete with the viscometer is placed vertically into the Dewar flask and both the tube and the flask are filled with ethanol; the temperature is kept at the desired level by adding carbon dioxide to ethanol.

To keep control over the temperature, one thermometer is inserted into the test tube and the other into the Dewar flask.

Industry uses laboratory mercury-in-glass thermometers for measuring temperatures from minus 30 to plus 150°C and alcohol-in-glass thermometers which can measure temperatures below minus 30°C.

In measuring the temperature in a constant-temperature chamber with a thermometer whose mercury or alcohol column extends outward beyond the chamber casing, one should apply a correction to the thermometer readings.

The correction Δt for a protruding mercury column is found from the formula

$$\Delta t = Kh (T_1 - T_2) \quad (10.11)$$

where K is a coefficient equal to 0.000 16 for the mercury thermometer and to 0.001 for the alcohol thermometer; h is the height of an outward-projecting mercury or alcohol column expressed in the number of divisions on the centigrade temperature scale; T_1 is the temperature in the chamber kept at a definite value for determining the viscosity of a test liquid, °C; and T_2 is the temperature of air around a mid-portion of the mercury or alcohol column extending outward, °C. The temperature T_2 is measured with a thermometer whose bulb is located in the middle of the height of the protruding column. The positive correction is subtracted from, and the negative is added to, the temperature in the chamber.

A viscometer intended for determining the kinematic viscosity of a test liquid shall be such that the liquid flows out for not less than 200 s. Prior to testing, the viscometer shall be thoroughly cleansed with an appropriate solvent and dried out. The liquid taken for testing shall be filtered out through a glass fiber or paper. The constant-temperature chamber is then adjusted for a temperature at which the viscosity of the liquid is to be measured.

The test procedure for determining the time of outflow of a test liquid in viscometers shown in Fig. 10.2*b* and *c* is as follows. Slip a rubber sleeve over a side tube 3. Now close a knee 2 with a finger, turn over the viscometer and lower a knee 1 into a vessel to suck in the test liquid with a rubber bulb until it reaches a mark M_2 , taking care that the air

does not get into the tube. As soon as the liquid approaches the mark M_2 , remove the viscometer from the vessel and quickly invert it into the normal position. Wipe out an excess of liquid on the outside of the knee 1 and slip a rubber sleeve over its end. Next place the viscometer into the constant-temperature chamber in such a manner that a bulb 4

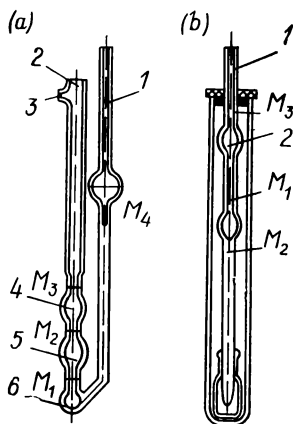


FIG. 10.3. Capillary viscometers

(a) BHЖ type for nontransparent liquids; (b) ВПЖМ type for testing small-volume samples

lies below the liquid level in the chamber. After holding the viscometer in the chamber for 15 min at a set temperature, suck in the liquid into the knee 1 until it rises to one-third the height of the bulb 4. Now let the knee communicate with the atmosphere and start the stopwatch to determine the time during which the meniscus of the liquid descends from M_1 to M_2 .

Consider now the procedure of determining the time of outflow of a liquid in a BHЖ viscometer (Fig. 10.3a). Fit a rubber sleeve over a side tube 3. Closing a knee 2 with a finger and inverting the viscometer, immerse a knee 1 into a vessel and suck in the liquid with a rubber bulb to a mark M_4 , making sure that the sucked liquid is free from air bubbles. As the liquid rises to a mark M_4 , take off the viscometer from the vessel and quickly turn it over into

the normal position. Wipe out an excess of liquid from the knee 1 and fit over its end an 8 to 15-mm long rubber sleeve with a closed cock or a clamp at its other end. Open now the cock to let the liquid fill a bulb 6 and then close it when the bulb becomes about half full. Place the viscometer into a constant-temperature chamber and hold it for a required length of time (20 min). Next open the knee 1 and start two stopwatches to measure the time of liquid outflow from M_1 to M_2 and from M_2 to M_3 .

The viscosity is calculated by the time it takes the liquid to fill the bulb 5. The time during which the liquid fills the bulb 4 is a control time. The former period of time may differ from the latter by 2% and even by 3% at a temperature below 15°C.

The test procedure with the use of a БИЖМ viscometer (Fig. 10.3b) comes to the following. Immerse a pipet 1 in a test liquid 1 or 2 mm below its level and suck it in up to a mark M_3 . Wipe out the pipet end to remove a drop of liquid and then gently lower the pipet into a receiving vessel. After assembling the device as shown in the figure, place it into a constant-temperature chamber for 30 min and then take the measurements. For this, using a rubber tube and a rubber bulb connected to the upper end of the pipet, draw in the liquid as far as a bulb 2 or a little higher and then allow the pipet to communicate with the atmosphere. Note the time during which the liquid column descends from a mark M_1 to a mark M_2 .

The use of any viscometer, excepting the БИЖ type, involves a few measurements of the time of test liquid outflow. Depending on the time t of testing, the number of measurements shall be equal to at least 5, 4, and 3 at t ranging from 200 to 300 s, 300 to 600 s, and over 600 s, respectively.

The kinematic viscosity ν of the material under test is calculated accurate to a fourth digit:

$$\nu = 1.019 \times 10^{-5} g \tau C K = C \frac{g \tau}{980.7} K \quad (10.12)$$

where C is the constant of a viscometer (given in the calibration test certificate); τ is the arithmetic mean of the time of outflow of a petroleum product, s; g is the free fall accele-

ration at the place of viscosity measurement, cm/s^2 ; 980.7 cm/s^2 is normal acceleration; and K is a coefficient allowing for changes in the hydrostatic pressure of a liquid due to its thermal expansion. For the БПЖ-1 type viscometer, $K = 1$; for the type БПЖ-2, БПЖ-4, and the Pinkevich viscometer, $K = 1 + 0.000\,040 \Delta t$; for the БНЖ type, $K = 1 + 0.000\,087 \Delta t$; for the БПЖМ type, $K = 1 + 0.000\,074 \Delta t$, where Δt is the difference between the temperatures of a petroleum product at the instant of its charging into the viscometer and at the instant of viscosity measurement. If Δt does not exceed 10°C , K may be taken to equal unity.

Using Table 10.2, we can convert from kinematic viscosity (m^2/s) to relative viscosity RV (deg.). At $\nu > 8 \times 10^{-5} \text{ m}^2/\text{s}$ (80 cSt), the formula suitable for converting from one system to the other is

$$\text{RV} = 0.135 \nu \quad (10.13)$$

The viscosity of liquids with a small time of outflow is determined by means of B3 viscometers primarily designed to measure the viscosity of electroinsulating varnishes (State Standards 8420-74 and 9070-75). The relative viscosity in this case is taken to be the time (in seconds) of continuous outflow of a definite volume of test liquid through a calibrated flow nozzle. The B3-1 type uses nozzles 2.5 and 5.4 mm in diameter. The B3-4 type has a 4-mm diameter nozzle for the measurement of viscosities in the range from 12 to 200 s.

Recording viscometers (State Standard 13368-73) find use for process control and automatization purposes, where there is a need for the continuous measurement of the viscosity of a liquid in a tank, bath, or in a pipeline, without taking samples or disturbing the course of a production process. Measurements are most often made here by means of electrical methods. This offers the opportunity, on the one hand, for remote measurement and convenient data recording, and, on the other, for the use of measuring devices as sensors in automatic control systems.

Some modified rotary viscometers with an electrical reference system and also ultrasonic (vibrating-plate) viscometers can be adapted for the continuous measurement of

TABLE 10.2

Conversion of Kinematic to Relative Viscosity (RV)

m ² /s	cSt	RV, deg.	m ² /s	cSt	RV, deg.
0.000 001	1.0	1.00	0.000 039	39.0	5.37
0.000 002	2.0	1.10	0.000 040	40.0	5.50
0.000 003	3.0	1.20	0.000 041	41.0	5.63
0.000 004	4.0	1.29	0.000 042	42.0	5.76
0.000 004 5	4.5	1.34	0.000 043	43.0	5.89
0.000 005	5.0	1.39	0.000 044	44.0	6.02
0.000 005 5	5.5	1.43	0.000 045	45.0	6.16
0.000 006	6.0	1.48	0.000 046	46.0	6.28
0.000 006 5	6.5	1.53	0.000 047	47.0	6.42
0.000 007	7.0	1.57	0.000 048	48.0	6.55
0.000 007 5	7.5	1.62	0.000 049	49.0	6.68
0.000 008	8.0	1.67	0.000 050	50.0	6.81
0.000 008 5	8.5	1.62	0.000 051	51.0	6.94
0.000 009	9.0	1.76	0.000 052	52.0	7.07
0.000 009 5	9.5	1.81	0.000 053	53.0	7.20
0.000 010	10.0	1.86	0.000 054	54.0	7.33
0.000 010 5	10.5	1.91	0.000 055	55.0	7.47
0.000 011	11.0	1.96	0.000 056	56.0	7.60
0.000 012	12.0	2.05	0.000 057	57.0	7.73
0.000 013	13.0	2.15	0.000 058	58.0	7.86
0.000 014	14.0	2.26	0.000 059	59.0	8.00
0.000 015	15.0	2.37	0.000 060	60.0	8.13
0.000 016	16.0	2.48	0.000 061	61.0	8.26
0.000 017	17.0	2.60	0.000 062	62.0	8.40
0.000 018	18.0	2.72	0.000 063	63.0	8.53
0.000 019	19.0	2.83	0.000 064	64.0	8.66
0.000 020	20.0	2.95	0.000 065	65.0	8.80
0.000 021	21.0	3.07	0.000 066	66.0	8.93
0.000 022	22.0	3.19	0.000 067	67.0	9.06
0.000 023	23.0	3.31	0.000 068	68.0	9.20
0.000 024	24.0	3.43	0.000 069	69.0	9.34
0.000 025	25.0	3.56	0.000 070	70.0	9.48
0.000 026	26.0	3.68	0.000 071	71.0	9.61
0.000 027	27.0	3.81	0.000 072	72.0	9.75
0.000 028	28.0	3.95	0.000 073	73.0	9.88
0.000 029	29.0	4.07	0.000 074	74.0	10.01
0.000 030	30.0	4.20	0.000 075	75.0	10.15
0.000 031	31.0	4.33	0.000 076	76.0	10.3
0.000 032	32.0	4.46	0.000 077	77.0	10.4
0.000 033	33.0	4.59	0.000 078	78.0	10.5
0.000 034	34.0	4.72	0.000 079	79.0	10.7
0.000 035	35.0	4.85	0.000 080	80.0	10.8
0.000 036	36.0	4.98	0.000 081	81.0	10.9
0.000 037	37.0	5.11	0.000 082	82.0	11.1
0.000 038	38.0	5.24	0.000 083	83.0	11.2

viscosity. These devices are capable of measuring the viscosity of very small samples, about 5 cm^3 in volume. The block diagram of an ultrasonic viscometer is shown in Fig. 10.4b. Current pulses, about $50 \mu\text{s}$ in length, pass through the excitation winding of a probe (Fig. 10.4a) immersed

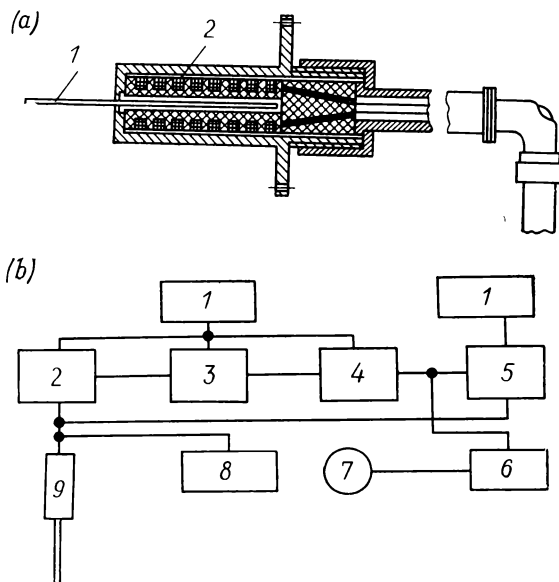


FIG. 10.4. Ultrasonic viscometer

(a) probe; 1—magnetostriuctive transducer; 2—excitation winding (b) block diagram; 1—electronic voltage stabilizers; 2—amplifier; 3—detector; 4—trigger circuit; 5—pulse generator; 6—pulse counter; 7—galvanometer; 8—probe magnetization current rectifier; 9—probe

in a test liquid and induce longitudinal ultrasonic oscillations of a plate which vibrates at a frequency of about 28 kHz. A superposed magnetization current applied to the winding adds to the probe sensitivity. Since the viscous medium absorbs the vibratory energy, the amplitude of vibrations of the plate and the emf induced in the winding decay with time by an exponential law. As the winding voltage decreases to a set value, a starting device comes into action, so that the probe winding receives the next current

pulse, and so on. Other conditions being equal, the pulse repetition rate measured by a counter will rise with an increase in the viscosity of a test liquid. This permits graduating the instruments in units of viscosity.

The continuous methods of viscosity measurement are highly convenient for determining the relationship between the viscosity of substances and temperature.

10.5. Atmospheric Durability

Atmospheric durability is the ability of an electrical insulating material to withstand atmospheric influences such as increased humidity, ozone, solar radiation, and atmospheric precipitation. Testing of materials in the conditions of high humidity was discussed in Sec. 7.3.

Apart from measuring electrical characteristics (E_{br} , ρ_v , R_i and R_{in}), tests of materials for moisture resistance involve the determination of such important parameters as moisture and water absorption and swelling (State Standard 10315-75).

The moisture and water absorption is determined from changes in the mass of a specimen after its exposure to moisture. The swelling of a material is found from changes in the geometrical dimensions of the specimen after its testing. Specimens are weighed in a tightly closed flask (weighing bottle, for example) and conditioned in an open specified medium. The time required for placing a specimen into the flask after its examination shall not be more than 30 s. The error in weighing the flask and specimens shall be kept within ± 0.001 g. Standards recommend the conditioning of specimens in the air at a relative humidity of $93\% \pm 2\%$ or $95\% \pm 2\%$ at $23^\circ\text{C} \pm 2^\circ\text{C}$, in the air of the same relative humidity at $40^\circ\text{C} \pm 2^\circ\text{C}$, and in distilled water at $23^\circ\text{C} \pm 0.5^\circ\text{C}$. These same standards (such as State Standard 4650-73 for plastics) prescribe the time of holding for each concrete material or component. After its exposure to moisture, the moisture shall be removed from the specimen with filter paper or a nonfluffy clean piece of cotton cloth.

The amount of absorbed moisture (in percent) referred to the mass of a dry test specimen before its moistening is

found from the formula

$$W = \frac{(m_1 - m_0)}{m_0} 100 \quad (10.14)$$

where m_0 is the mass of the dry specimen before its placing into a test chamber, mg; and m_1 is the mass of the specimen after its conditioning in the humid atmosphere.

The water absorption in percent is calculated by the formula

$$H = \frac{(m_2 - m_0)}{m_0} 100 \quad (10.15)$$

where m_0 is the mass of the dry specimen before its immersion in water; and m_2 is the mass of the specimen after its removal from water and wiping.

Plastics are also checked for the amount of water-soluble components, X :

$$X = \frac{(m_0 - m_3)}{m_0} 100 \quad (10.16)$$

where m_0 is the mass of the dry specimen before its immersion in water; and m_3 is the mass of the specimen after its holding in water and second drying.

In tests for moisture and water resistance, the swelling of a specimen is determined by measuring its width (diameter) and thickness at five points near the edges; the measurement error shall be within ± 0.01 mm. The specimen is measured before and after its holding in the humidity chamber or in water. The swelling is expressed as the arithmetic mean of percentage changes in the width and thickness of the specimen measured at five points after exposure to the test medium. At least three specimens shall be tested to determine the stability of the material to swelling.

Testing of materials and components for resistance to a corona and corona-produced ozone was discussed earlier in Sec. 6.1. It should be added that ozone, being a powerful oxidizing agent, strongly attacks most of the organic dielectrics and primarily impairs their physicochemical properties. For this reason special tests are often conducted to determine the resistance of materials to ozone.

For example, according to State Standard 9.026-74, rubbers are subjected to static or dynamic tensile stresses in

an ozonized air with a set concentration of ozone at a temperature of $30^{\circ}\text{C} \pm 2^{\circ}\text{C}$ or $50^{\circ}\text{C} \pm 2^{\circ}\text{C}$. The parameters that determine the stability of resins to ozone are: (a) the length of time τ_{cr} before the appearance on the surface of a specimen of first cracks seen by the naked eye; (b) the length of time τ_r before the rupture of a specimen; (c) the coefficient of ozone aging, $K_o = P_2/P_1$, where P_1 and P_2 are the tensile strength of a specimen before and after exposure to ozone respectively; (d) the maximum concentration of ozone, C_{max} , at which the specimen does not yet develop cracks during the specified period of time. The specimens used for determining τ_{cr} and C_{max} shall measure $120 \times 10 \times 2$ mm and the specimens for determining τ_r shall be 120 by 10 by 0.5 mm plates with an edge radius of 0.2 mm. Specimens for estimating K_o are made in the form of blade-type test pieces cut out from strips 10 to 25 mm wide and $1.0 \text{ mm} \pm 0.1 \text{ mm}$ or $2.0 \text{ mm} \pm 0.2 \text{ mm}$ thick (State Standard 270-75). The number of specimens shall be not less than 5. The tests shall be started not earlier than 16 h and not later than 30 days after rubber vulcanization.

The properties of materials undergo heavy changes on prolonged exposure to visible light, in particular when oxygen of the air is gaining access to the bulk of insulation. The shorter the wavelength, that is, the higher the energy of a light quantum, the stronger the effect of solar radiation on a material. Ultraviolet rays are very detrimental to many organic materials; they decrease the mechanical strength and elasticity of insulation, cause the formation of cracks, peeling of varnish films from substrates, and promote other defects. It is important to note that in a number of cases the effect of visible and ultraviolet rays on organic materials resembles by its character an oxidizing aging, in particular, ozone-induced aging. Electrical insulation in service often experiences a simultaneous action of a number of detrimental factors.

State Standard 6992-68 prescribes tests on paint coatings which involve prolonged exposure to visible light or ultraviolet light and simultaneous exposure to the air, moisture, and atmospheric precipitation. Such tests can be accomplished simply by keeping specimens in the open air on special platforms on factory roofs or on the ground, where they are

exposed to sunlight, rain, wind, and other influences. At certain intervals of time, the specimens are examined, photographed if necessary, and checked for discoloration, change in mass, peeling, cracking, and other defects.

Similar tests can be done in an accelerated manner, using special weathering test units, called weatherometers. A weatherometer exposes specimens to intensive ultraviolet light (from a quartz lamp or any other source) and to the air (humid air too, if required).

State Standard 17471-71 prescribes the technique of testing plastics in weatherometers. Carbon arc lamps of the closed type or glow-discharge xenon lamps serve as a source of light radiation whose spectrum is close to that of solar radiation on the Earth's surface at noon in June (the wavelength is 300 to 400 nm and the radiant flux in the near ultraviolet region is 69.78 W/m^2). A weatherometer also has a sprinkler and a temperature and humidity control system. The time of weathering may vary with the type of test specimen (the standard usually specifies the time of testing). After weathering, the specimens for plastic materials are thoroughly examined, wiped off with a clean cotton cloth, conditioned, and then subjected to mechanical, electrical or other tests.

Polymer films are tested for stability to light-heat aging in special apparatus (State Standard 8979-75). Film specimens are placed in a test chamber and irradiated by a mercury-quartz radiation source ПРК-2 rated at 375 kW; the drum 0.4 m in diameter provides for rotation of the specimens about the radiation source at a speed of 1 rpm. At the same time, heaters can raise the temperature in the chamber if necessary and a sprinkler can moist the specimens. The chamber also has a mercury thermometer for temperature control and a fan for air mixing. The test conditions (the time of aging and rest, temperature, and other factors) may vary depending on the type of material being tested. After the test is completed, the specimens are conditioned and the desired parameters determined (such as mechanical durability, cold resistance, and other characteristics).

One of the accelerated weathering test methods involves holding of test specimens in a solar test apparatus provided with a few electropolished-aluminum mirrors which reflect

the sunlight and direct it at the specimens mounted on a stand. The servo system turns the mirrors in step with the Sun's motion. This technique of testing plastics on a solar stand is covered in detail in State Standard 13916-68.

Sources of ultraviolet radiation are special discharge lamps containing a mercury vapor kept at a certain pressure; they emit light when an electric discharge arises in the mercury vapor. Such a lamp has a transparent envelope made from quartz or any glass that passes ultraviolet rays, a firing element to start a discharge (the firing voltage is about twice the working voltage), and other control and protective elements. The light emitted by the lamp goes through a glass, plastic, or liquid-type light filter that passes ultraviolet rays of a definite wavelength range but intensively absorbs visible light, for which reason the filtered ultraviolet light is sometimes called a black light. An example of the glass composition for such a filter is: 50% SiO_2 , 25% BaO , 16% K_2O , 9% NiO . Tests for determining the effect of ultraviolet rays on materials can be conducted with the aid of fluorimetric analysis devices having a powerful source of ultraviolet radiation.

While observing electrical insulating materials in the black ultraviolet light, we can see that each exhibits its own characteristic hue of luminescence. Thus various petroleum oils give definite tints of the violet, blue, dark blue, and green. The available kinds of paraffin also differ in coloration. The same also concerns resins and rubbers: the raw linseed oil looks olive and the boiled type gray brown; natural rubber produces a light brown color and butadiene-styrene rubber a light blue that, given a definite degree of treatment, changes into a dark blue and then into a brown. When observing threads of various materials exposed to ultraviolet radiation one can readily differentiate cotton fiber, that does not emit light, from silk and wool; it is also easy to tell natural silk from artificial silk in ultraviolet light. Pure cellulose-base paper gives a light yellow color and wood pulp-base paper a violet color.

In testing materials for atmospheric durability under given conditions (at a definite temperature, humidity, gas composition, and pressure), specimens are given a certain dose of solar radiation. In accelerated weathering tests, speci-

mens are also exposed to ultraviolet radiation. The specimens are then checked for changes in mechanical and electrical characteristics. Apart from the detection of irreversible changes in the properties of materials after exposure to radiation, of much interest is the determination of electrical properties of materials in the course of irradiation, though this type of testing involves considerable difficulties and necessitates special test equipment. It should be kept in mind that, apart from other factors, a medium itself (air, neutral gas, or vacuum) has a considerable effect on changes in the properties of a material.

While attending fluorimetric analysis devices and weatherometers, the operators shall observe the prescribed safety rules. Safety precautions shall be adequate to preclude accidents. Thus the casing of a light source shall be grounded and the lamp fixture insulated from the casing. To avoid cuts with glass splinters and poisoning by mercury vapors when a lamp envelope bursts, it is impermissible to switch on high- and super-high-pressure lamps if they do not have a protective casing. Ultraviolet rays, particularly short-wave and medium-wave rays, adversely affect the man's organism. Looking at an unshielded glowing mercury lamp even for a short time may cause a burn of the eyes; the attendants servicing devices with open lamps shall wear goggles and face guards from dense cloth. Discharge lamps in service heavily ionize the air that becomes laden with ozone and nitrogen oxides. Whenever there is a smell of ozone, the room shall be given good airing. Proper airing is also necessary in case of breaking or bursting of a lamp in order to remove mercury vapors which are very harmful to the man's health.

TROPICAL RESISTANCE

11.1. General

Electrical equipment and insulating materials in particular operate under adverse conditions in the tropical climate, whether humid or dry.

The humid tropical climate combines high relative humidity with increased temperature: the relative humidity of air exceeds 80% at over 20°C and remains so for no less than 12 hours a day during a period of two or more months in the year. Typical of the tropics are copious cloud-bursts (the rainfall may reach 100 mm in 10 min), strong solar radiation, and detrimental biological factors (the effects of fungi, insects, termites in particular, and rodents on the life of insulation).

The dry tropical climate is inherent in plains and deserts which have high air temperature, up to 55°C in the shade, increased solar radiation at a comparatively low relative humidity, and strong winds that contaminate the air with dust and sand. Biological factors here also play a certain role, though the growth of fungi is not typical for the dry tropical climate.

Electrical engineering materials and products, including electrical insulating materials, are considered tropic-resistant if they stand the above adverse influences and retain their properties.

Tests for tropical resistance are conducted in compliance with the recommendations of the International Electrotechnical Commission (IEC) and as prescribed by the standards and specifications on materials and components. The types of test on materials and components designed for work in tropical regions are covered in State Standard 15963-70. Tropical-exposure tests determine the following characteristics of materials: the moisture resistance, thermal endurance, fungus (mold) resistance, solar radiation stability, sea fog resistance, cold resistance, waterproofness, and dustproofness.

Test conditions differ with the category of a product and the function it must perform. In Sections 9.4, 9.5, and 10.5, we have considered these conditions (the temperature, humidity, duration, and cycle of testing) for a number of tests. The tropical resistance of a material or component can be judged by changes in the electrical and physicomachanical properties of the specimen subjected to tropical-exposure tests.

11.2. Fungus Resistance

In the tropical climate, the growth of fungi on the surface of a material strongly affects its properties. The kinds of mold most harmful to organic insulation are: *Aspergillus niger*, *Aspergillus amstelodami*, *Paecilomyces varioti*, *Stachybotrys atra*, *Penicillium cyclopium*, *Penicillium brevicompactum*, *Chaetomium globosum*, *Trichoderma lignorum*. The detrimental effect of mold shows up in the following: (a) the current-conducting paths that appear on the surface of a material heavily reduce its surface resistance and can even lead to a decrease in its volume resistance; (b) the products of activity of fungi react with a material and thus impair its electrical properties; and (c) the filaments of mold absorb and keep water, which also has a destructive effect on the properties of a material or component.

The effective means for raising the fungus resistance of materials are fungicides added to the composition of materials or applied to their surface. Fungicides are substances poisonous to fungi, so they retard the fungus growth. Examples of fungicides are hydroxydiphenyl, cupric pentachlorophenolate, cupric 8-hydroxyphenolate, and other substances.

State Standards 9.048-75, 9.049-75, 9.050-75, and others cover in detail the methods of test for determining the fungus resistance of materials and components. By these methods, the material under test is infected with spores of fungi and then held for a definite time under the conditions favorable for the growth of mold.

A fungus culture is first grown in a nutrient medium such as a dry wort with an addition of agar-agar or in a special culture medium, for example, Czapek's medium of the com-

position: 1 l distilled water, 20 g agar-agar, 0.55 g magnesium sulfate, 0.7 g monopotassium phosphate, 0.3 g dipotassium phosphate, 0.5 g potassium chloride, 0.01 g ferrous sulfate, 2.0 g sodium nitrite, and 30 g sucrose. The pH value of the culture medium shall be equal to 6 ± 0.5 .

The culture medium is prepared in a boiling water bath. The ready hot medium is poured out into test tubes, 4 or 5 ml into each, with the tube edges kept dry to avoid contamination of the medium by foreign microorganisms. The tubes closed with cotton plugs are sterilized in an autoclave at a steam pressure of 50 kPa and a temperature of 112°C for 20 to 30 min.

The tubes, one-third full of the sterile medium, are placed at an angle of $25^{\circ} \pm 5^{\circ}$ to the horizontal to have the surface of the medium slanting after its solidification. The solidification takes place at $20^{\circ}\text{C} \pm 5^{\circ}\text{C}$. Pure fungus cultures are then cultivated on the surface of the nutrient medium in a special sterile box.

Inoculation of the culture medium is carried out with an ansa (loop) or needle $0.6 \text{ mm} \pm 0.1 \text{ mm}$ in diameter and $120 \text{ mm} \pm 2 \text{ mm}$ in length, made from a heat-resistant metal (platinum, chromium, nickel, and molybdenum). The needle is sealed or soldered in a glass or metal holder. The needle end bent at a right angle into a knee 3 mm in length serves as a scraper for the transfer of spores. Before inoculation, the needle is sterilized in the flame of a burner. The upper edges of the tube and its outer surface are treated against germs after inoculation. The tubes inoculated with spores are placed in an exiccator at $29^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and held there until the appearance of mature sporulation. The permissible time of holding of a culture in the refrigerator at a temperature of $\pm 3^{\circ}\text{C}$ is 6 months.

Before testing a material or component for fungus resistance, it is necessary to wash off the spores of fungi from each pure culture with distilled water; the water containing spores of all the eight kinds of fungus at the age of 14 to 28 days is poured into a common flask and then used for contamination of specimens within 6 h. The accessible surfaces of specimens are uniformly sprinkled with the suspension of fungus spores and left to stay in the box at $25^{\circ}\text{C} \pm 10^{\circ}\text{C}$ and 80 % relative humidity until the evaporation of

drops, but not longer than 60 min. Next the specimens, together with the reference samples of culture media contained in sterile Petri dishes are put in an exiccator and placed not less than 20 mm apart and 50 mm away from the exiccator walls. The growth of fungi in the culture media is indicative of soundness of the spore suspension. The air in the exiccator chamber is kept at a temperature of $29^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and relative humidity of over 90 % to provide for a most favorable growth of fungi. The test lasts 28 days beginning at the moment when the test conditions have become stable. Every 7 days the exiccator cover is taken off for 3 min to allow the fresh air to flow into the chamber.

After the test is over, the specimens are removed from the chamber and examined right away by the naked eye in the diffused light at a luminance of 2 000 to 3 000 lx. The specimens are then observed under a $\times 50$ to 60 microscope and photographed if necessary. The fungus resistance is estimated by referring to the following six-index scale:

No growth of fungi is seen under the microscope	0
Grown spores and a weakly developed mycelium in the form of branched hyphae are seen in the microscope . . .	1
The mycelium as a mass of branched hyphae, indicative of possible sporulation, is seen in the microscope	2
The growth of fungi is hardly visible by the unaided eye, but clearly discernible under the microscope	3
The growth of fungi covering about 25 % the specimen surface is clearly visible by the unaided eye	4
The growth of fungi covering over 25 % the specimen surface is clearly seen by the unaided eye	5

The appendix to State Standard 9.048-75 contains the photographs of specimens that can serve as a reference in estimating the fungus resistance of a material by the six-index scale.

Along with fungi, insects such as termites present a hazard to a material since they gradually destroy it. Tests for termite resistance are performed under natural conditions (in termites' nests of Turkmenistan) in conformity with State Standard 15158-78. The specimens for paper and press-board, at least ten specimens for each type, cut in the form

of a strip 80 mm wide and densely rolled into a tube 25 mm in external diameter, are dug to a depth of 10 to 20 cm on the eastern, southern, and western sides of the nests of termites and held there for 6 months, from April to November inclusive. The specimens are then visually examined for damage. The material is considered to have passed the test if termites have destroyed not more than 10% of specimens.

11.3. Sea Fog Resistance

The tests for sea fog resistance determine the stability of a material to the corrosive effect of an atmosphere saturated with aqueous salt solutions.

Specimens are placed in a chamber kept at $27^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and subjected to the action of a saline fog formed by centrifugally spraying or atomizing a solution of sodium chloride in distilled (deionized) water with a concentration of $33 \text{ g/l} \pm \pm 3 \text{ g/l}$. The dispersivity of fog is 1 to $10 \text{ }\mu\text{m}$, with a water content of 2 or 3 g/m^3 . The solution is sprayed for 15 min at 45-minute intervals. After testing, the specimens are washed in distilled water, dried at $55^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 1 h, cooled, and checked for the requisite characteristics as prescribed by the standard.

RADIATION RESISTANCE

•

12.1. General

Radiation resistance is the characteristic of a material that enables it to retain useful properties on exposure to ionizing radiation, that is, radiation having sufficient energy to produce ions by dislodging electrons from atoms. Among various kinds of this radiation, the most hazardous to electrical insulating materials are gamma radiation and neutron radiation capable of propagating through a substance to a large depth, of the order of several tens of centimeters. The electrical insulating materials used in nuclear reactors are exposed to a few emissions simultaneously, of which gamma and neutron fluxes play the main role.

Gamma radiation is a penetrating short-wave electromagnetic radiation which represents a flux of gamma-quanta. Neutron radiation is the emission of a flux of neutrons varying in energy w_n . The energy w_n of thermal, near-thermal, intermediate, and fast neutrons respectively equals 0.025 eV, 0.1 or 0.2 eV, about 2×10^5 eV, and 2×10^5 eV to 2×10^7 eV. In an ionizing neutron flux, intermediate and fast neutrons play a most active part.

Materials and products exposed to ionizing radiation can undergo irreversible changes and reversible (induced) changes that show up only during radiation. Reversible changes primarily depend on the intensity of radiation, and irreversible changes on the total quantity of radiant energy (called a dose) absorbed by a unit mass of substance. In the SI, the unit of radiation dose is a joule per kilogram (1 J/kg), that is a radiant energy of 1 J transported to a substance 1 kg in mass. The cgs unit of radioactive dose of exposure, still used sometimes in practice, is the roentgen (R): 1 R is the amount of gamma- or X-radiation that will produce one electrostatic unit of charge (of each sign) in one cubic

centimeter of dry air at a pressure of 101.325 kPa (760 mm Hg) and a temperature of 0°C.

The quantity, called a radiation-exposure dose, characterizes radiation by the degree of ionization it produces. The SI unit of radiation-exposure dose is a coulomb per kilogram (C/kg), which is the amount of radiation that produces ions with a total charge of 1 C (of each sign) in 1 kg of dry air. Since the mass of 1 cm³ air is equal to 1.293×10^{-6} kg, then, considering the relation between the coulomb and the cgs unit of charge, $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$, $1 \text{ C/kg} = 3.88 \times 10^3 \text{ R}$.

Measuring the dose of radiation by its ionizing capacity permits us to establish the physical equivalent of the unit of radiation dose, which bears the name of rep (roentgen-equivalent-physical): 1 rep is the dose of gamma radiation that imparts such an energy to 1 g of substance as to enable it to emit the energy equivalent to the energy spent on the ionization of 1 g of air. Under standard conditions, $1 \text{ rep} = 0.97 \text{ R} = 85 \text{ ergs/g}$.

In practical use is also another unit of absorbed radiation dose, known as rad, which is equivalent to an energy of 0.01 J that the gamma radiation imparts to 1 kg of irradiated matter: $1 \text{ rad} = 0.01 \text{ J/kg} = 100 \text{ ergs/g} = 1.15 \text{ R}$.

The dose rate is the intensity of radiation per unit time. The unit of dose rate is a watt per kilogram (W/kg) and a rad per second (rad/s): $1 \text{ rad/s} = 0.01 \text{ W/kg}$; $1 \text{ rad/h} = 2.78 \times 10^{-6} \text{ W/kg}$.

The density of a neutron flux (of intermediate and fast neutrons) is the number of neutrons that will pass through a unit area (1 cm², 1 m²) of an irradiated body at a right angle to its surface. The neutron unit of dose (N-unit) is the amount of neutron radiation that produces a total charge of 1 C in a human tissue equivalent gas of 1 kg. The composition of this gas is: 64.4% methane, 32.5% carbon dioxide, and 3.1% nitrogen. The effect of neutron radiation on such a gas is similar to the effect it has on organic substances since in both cases the neutron flux destroys organic molecules.

The roentgen-equivalent-man (rem) is used in practice to estimate the biological effect of radiation. This is an exposure dose of neutron radiation with $w_n \geq 0.1 \text{ MeV}$,

which produces the same effect on human tissue as one roentgen of gamma radiation. Under these conditions, 1 rem is equivalent to a density of integral neutron flux of $7 \times 10^7 \text{ cm}^{-2}$.

In general form, it is impossible to give the relation between the gamma radiation dose units and neutron radiation dose units because materials differ in the intensity of absorption of these two kinds of energy.

Electrical insulating materials exposed to ionizing radiation undergo changes in electrical, physicochemical, and mechanical properties, often attended by gas evolution and the formation of new substances. At large doses of radiation, a material may decompose completely.

The methods of test that determine the characteristics of materials undergoing reversible changes in properties differ substantially from the methods for determining the characteristics which change irreversibly under irradiation. Such electrical characteristics of a material as ρ , ϵ , $\tan \delta$, and E_{br} often regain their original values some time after removal of the radiation flux. For this reason they are measured under irradiation. Consider some methods of detecting changes in electrical properties of materials exposed to radiation.

12.2. Characteristics of Materials Exposed to Radiation

What complicates radiation-exposure tests is the necessity of installing measuring equipment a considerable distance away from the source of radiation, while placing a test specimen in close vicinity to the source. The task of determining reversible changes in specimens exposed to radiation involves the periodic measurement of such basic quantities as C , $\tan \delta$, R_x , and U_{br} . In a measuring unit, a shielded cable connects the electrodes of a specimen to instruments placed at a safe distance from the radiation source. During radiation, the resistance of cable insulation shall have 100 times the specimen resistance R_x which is measured by common methods (see Ch. 1).

The capacitance C_{cab} and loss tangent $\tan \delta_{cab}$ of the cable introduce an additional error in the measurement results, in

particular at 1 000 Hz and above. But it is possible to allow for the effect of C_{cab} and $\tan \delta_{cab}$ by measuring the quantities twice, once with the specimen connected in the measuring circuit and the second time with the specimen disconnected from the circuit (see Sec. 4.3). The measurements are performed with the aid of a remote handling unit.

Another method of measurement uses a differential unbalanced bridge which permits taking readings of C_x and

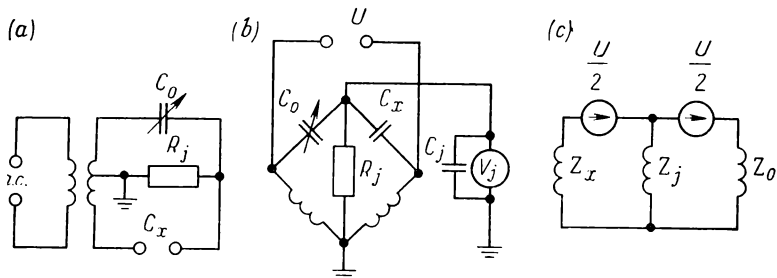


FIG. 12.1. Differential unbalanced bridge circuits
(a) and (b) circuit diagrams; (c) calculation diagram

$\tan \delta$ continuously without disconnecting the specimen, which is a particular advantage since this offers the opportunity for evaluating changes in ϵ and $\tan \delta$ of materials during irradiation (Fig. 12.1). Two arms of the bridge are a pair of secondary half-windings of a differential transformer, the third arm is a standard variable capacitor C_0 , and the fourth is a test specimen C_x . A standard high d.c. resistance R_j is connected across the opposite junctions of the arms; the voltage across the junctions is measured with a voltmeter V_j having a high-resistance input and low input capacitance C_j . The advantages of this method are the presence of only one controllable element—the standard capacitor—and the possibility of taking readings of $\tan \delta$ from the scale of a pointer instrument that measures U_j across the opposite junctions of the bridge. This voltage is proportional to the difference in currents flowing through the capacitors of capacitance C_0 and C_x . If these capacitances

are equal

$$C_0 = C_x \quad (12.1)$$

the voltage U_j is at a minimum and is due to the loss in the capacitor, C_x , because the loss in the capacitor, C_0 , is negligible. Let us show that the readings of the voltmeter with a high-resistance input and low input capacitance are proportional to $\tan \delta$ of the specimen. Using the node-voltage method, we determine the voltage across the opposite pair of junctions (Fig. 12.1c):

$$\dot{U}_j = \frac{U}{2} \frac{1/Z_x - 1/Z_0}{1/Z_x + 1/Z_0 + 1/Z_j} \quad (12.2)$$

where U_j is the complex voltage for the unbalanced bridge circuit:

$$Z_0 = -j \frac{1}{\omega C_0}, \quad Z_x = \frac{1}{\omega C_x} (\tan \delta - j) \quad (12.3)$$

Z_j is the impedance of the voltmeter.

Because $C_0 = C_x$, while

$$1/Z_j \ll 1/Z_x + 1/Z_0 \quad (12.4)$$

then, after substitution into Eq. (12.2), we have

$$\dot{U}_j = \frac{U}{2} \frac{\frac{\tan \delta}{\omega C_x} - j \frac{1}{\omega} \left(\frac{1}{C_x} - \frac{1}{C_0} \right)}{\frac{\tan \delta}{\omega C_x} - j \frac{1}{\omega} \left(\frac{1}{C_x} + \frac{1}{C_0} \right)} \quad (12.5)$$

Since $C_x = C_0$, then

$$\dot{U}_j = \frac{U}{2} \frac{\tan \delta}{\tan \delta - 2j} \quad (12.6)$$

The modulus of complex voltage across the junction of the bridge is

$$U_j = |U_j| = \frac{U}{2} \frac{\tan \delta}{\tan^2 \delta + 4} \sqrt{\tan^2 \delta + 4} \quad (12.7)$$

At $\tan \delta \ll 0.1$, it is quite safe to write that

$$\tan \delta \approx 4U_j/U = kU_j \quad (12.8)$$

Since the supply voltage remains invariable, the scale of the voltmeter can be calibrated in terms of $\tan \delta$.

The procedure of measurements is as follows. Setting up the specified frequency and voltage U , adjust the variable

capacitor C_0 for a minimum reading of the pointer instrument. Now take a reading of C_0 on the dial which gives the value of C_x and note the reading of the pointer instrument which indicates the value of $\tan \delta$. The measuring circuit often incorporates an amplifier with a high-resistance input to ensure an adequate sensitivity of the measuring device.

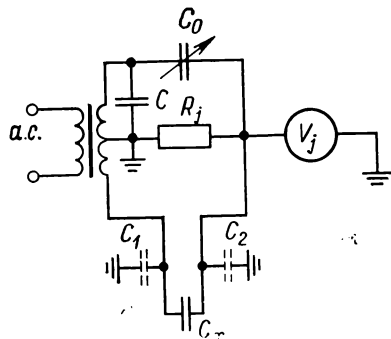


FIG. 12.2. Differential bridge circuit for remote-testing of a specimen

Where a cable connects a test specimen to the bridge (Fig. 12.2), additional stray capacitances C_1 and C_2 may appear, which affect the measurement results. The effect of C_1 can be offset by inserting an additional capacitance $C = C_1$ in the circuit. The capacitance C_2 is placed in parallel with the pointer instrument, which makes it necessary to express $\tan \delta$ in a different manner than when the measurements are made without the connecting cable:

$$\tan \delta = \frac{4U_j}{U} \left(1 + \frac{C_2}{C_x} \right) \quad (12.9)$$

The cable capacitance C_2 to ground can be measured in advance. The capacitance C_x is read from the dial of the standard capacitor when the pointer instrument indicates the lowest possible value of $\tan \delta$. The differential bridge can measure quantities in the frequency range between 100 Hz and 200 kHz. The capacitance of a test specimen shall be in the order of 200 pF, with its $\tan \delta$ ranging from 10^{-3} to 10^{-1} . The measurement error lies within the permissible limits.

Determining the breakdown voltage of a solid material under radiation involves the replacement of a ruptured specimen by a sound specimen that has taken the same dose

of radiation. A magazine containing from 6 to 24 specimens simultaneously irradiated by the same source can give a good illustration of changes in the dielectric strength of the material under test. After breakdown of a test specimen and decrease in voltage, a switching device with a servomotor located in the zone of diffused radiation connects the high-voltage terminal of the test voltage cable to the electrode of the next specimen. The a.c. breakdown voltage of specimens is measured periodically in the course of radiation.

12.3. Characteristics of Materials After Irradiation

The irradiated specimens are checked for various characteristics after their removal from the radiation-exposure chamber. The methods of test do not differ from the common methods for determining the electrical characteristics of materials. It should be kept in mind, however, that the reversible radiation-induced changes in the properties of a material disappear gradually, for which reason it is necessary to note the time of measurement. Time measurement is started at the moment when the irradiation of a test specimen has ceased. A need often arises for the periodic measurements of, say, conductance to determine its change with time, that is, the rate of "curing" of structural defects that have developed under irradiation.

A second important factor is the effect of temperature on reversible radiation-induced changes. At an increased temperature, self-healing generally proceeds in a manner different from that at normal temperature, so it is important to hold the test temperature at a present level. The use of sources of radiation noted for high-energy particles may cause activation of specimens, electrodes, holders, and other elements, which themselves become the sources of radiation for some time after their removal from the radiation chamber and may present a hazard to the personnel.

The isotope of cobalt ^{60}Co often finds use as a source of gamma radiation; in this case, dielectrics with low atomic numbers of the constituent elements practically show freedom from activation. In testing other materials and com-

- GOST 17170-71. Plastics. Methods of test for aging under natural climatic conditions.
- GOST 17171-71. Plastics. Methods of test for ageing under artificial climatic conditions.
- GOST 13916-68. Plastics. Accelerated method of test on solar stand for stability to sunlight.
- GOST 8979-75. Artificial leather and film materials. Methods for determining stability to heat and lighthouse aging.
- GOST 15963-70. Electrical engineering products for work in tropics. General specifications.
- GOST 9048-75. Technical products. Laboratory tests for fungus resistance.
- GOST 12370-80. Piezoceramic materials. Test methods.
- GOST 2214-78. Electroinsulating varnished cloth.
- GOST 17675-80. Flexible insulating tubes.
- GOST 14340-69. Enamelled wires. Test methods.
- GOSTs 2990-72, 10786-72, 12177-72, 17397-72, 3345-76, 7229-76, 12180-76. Cables and wires. Test methods.
- GOST 24602-81. Paper capacitors.

ponents such as electrolytic tantalum capacitors for radiation resistance, the danger of activation may become apparent and thus should be reckoned with.

The tests of materials for resistance to ionizing radiation necessitate checking not only electrical characteristics but also physical parameters such as mass, gas evolution, the viscosity and color of liquid dielectrics, and acidity of oil.

While running these tests, the operating personnel shall strictly observe safety rules. According to "Basic Sanitary Rules of Handling Radiactive Substances and Other Sources of Ionizing Radiation" adopted by the State Sanitary Commission in 1972 and "Norms and Rules of Radiation Safety" approved by the USSR Ministry of Public Health in 1976, the radiating power (dose rate) acting on the surface of a block that contains radiation source shall not exceed 10 mR/h and shall be not over 0.3 mR/h at a distance of 1 m. A higher dose rate is permissible for gamma-ray flaw detectors on condition that the exposure dose for the attendants does not exceed 0.1 R for a week.

At an office or plant, the director appoints a supervisor whose task is to carry into effect the instructions drawn up for operating units and devices which incorporate radiation sources and also to see to it that the personnel strictly observe safety rules.

Laboratories shall have dose-meters for control of the level of radiation. Soviet industry puts out personal radiation monitoring sets for measuring roentgen and gamma radiation over the ranges from 0.02 to 0.2 R and 0.2 to 2 R at an energy of 0.15 to 2 MeV. The measurement error does not exceed $\pm 10\%$ under normal conditions.

APPENDIX

.

Basic USSR State Standards (GOSTs) on Testing Electrical Insulating Materials and Components

- GOST 21515-76. Dielectric materials. Terms and definitions.
- GOST 6433.1-71. Solid electrical insulating materials. The environment in preconditioning, conditioning, and testing.
- GOST 6433.2-71. Solid electrical insulating materials. Methods for determining electric resistances at d.c. voltage.
- GOST 6433.3-71. Solid electrical insulating materials. Methods for determining dielectric strength at a.c. (50 Hz) and d.c. voltage.
- GOST 6433.4-71. Solid electrical insulating materials. Methods for determining loss tangent and permittivity at 50 Hz.
- GOST 6581-75. Liquid electrical insulating materials. Electrical test.
- GOST 22372-77. Dielectric materials. Methods for determining loss tangent and permittivity at from 100 to 5×10^6 Hz.
- GOST 10345.1-78. Solid electrical insulating materials. Methods for determining arc resistance at above 1 000 V a.c.
- GOST 12423-66. Plastics. Conditioning of specimens (samples).
- GOST 14359-69. Plastics. Mechanical testing procedures. General requirements.
- GOST 21555-76. Solid electrical insulating materials. Methods for determining stability to surface tear.
- GOST 4670-77. Plastics and ebonite. Ball-indentation hardness test at preset load.
- GOST 15634.2-70. Magnet wire coated with fiber and enamel-fiber insulation. Method of test of insulation for abrasion resistance.
- GOST 8865-70. Electrical insulating materials for electrical machines, transformers, and apparatus. Classification by thermal endurance.
- GOST 11506-73. Petroleum bitumens. Ring-and-ball method for determining softening point.
- GOST 15065-69. Plastics. Vicat softening point test in atmosphere.
- GOST 21341-75. Plastics and ebonite. Martens heat-stability test.
- GOST 13921-68. Organic chemical products. Flash and fire point test in open tank.
- GOST 13526-68. Electrical insulating varnishes and enamels. General methods of test.
- GOST 12020-72. Plastics. Methods for determining resistance to attack by chemical media.
- GOST 8420-74. Paintwork materials. Methods for determining relative viscosity.
- GOST 10315-75. Solid electrical insulating materials. Moisture and water resistance tests.

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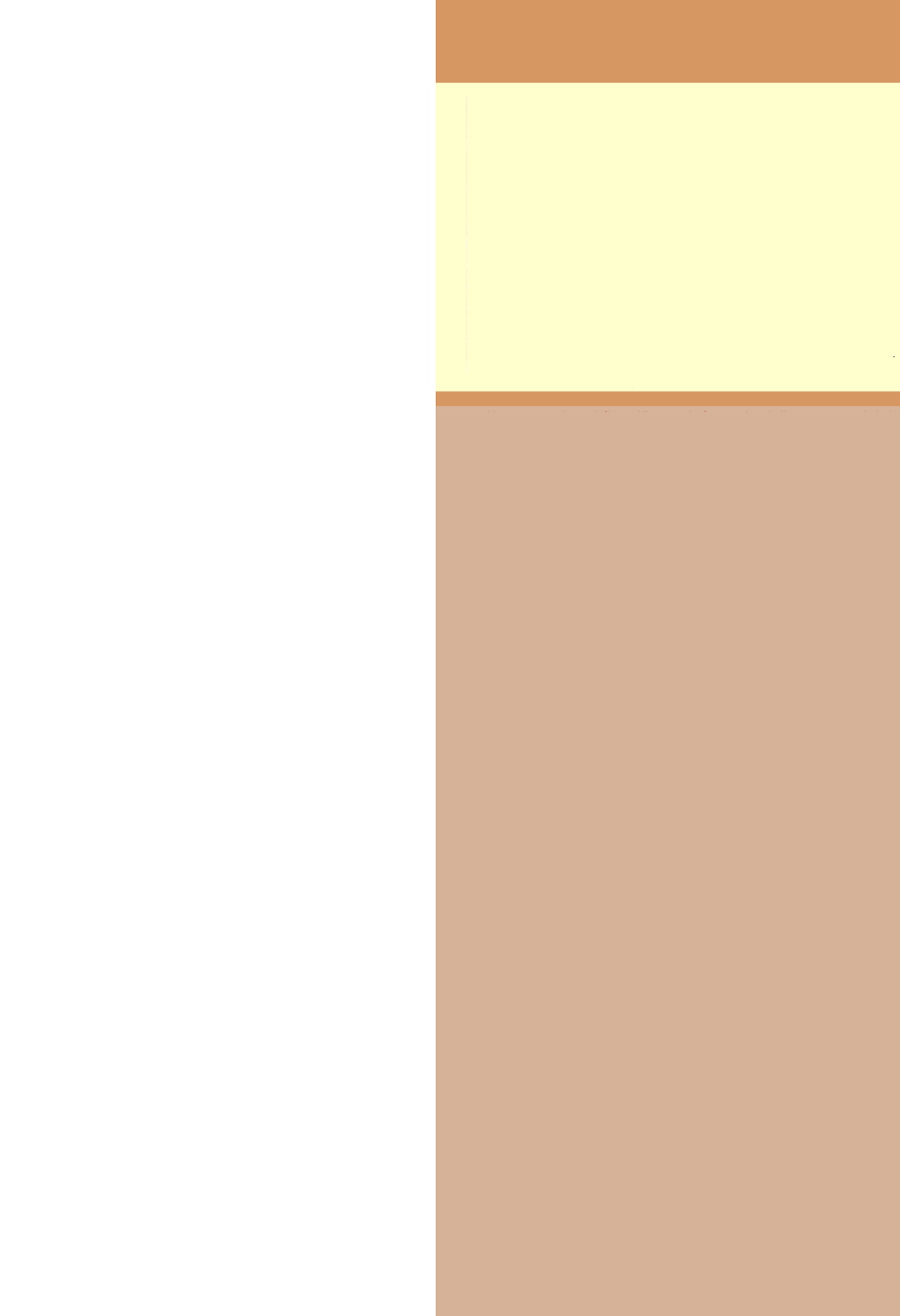
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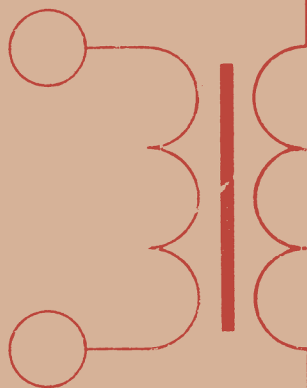
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